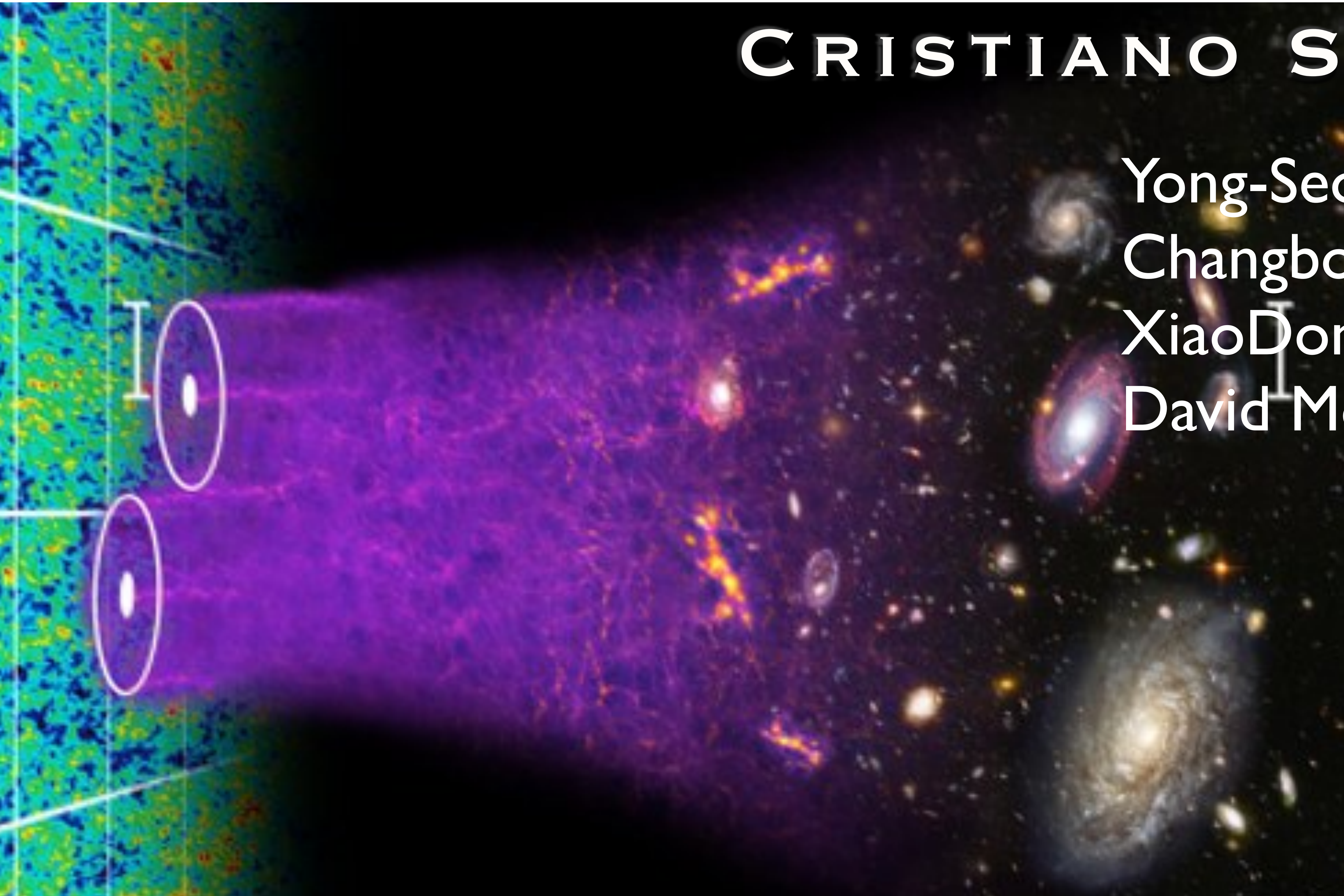
Cosmology from the Clustering Statistics of the Large Scale Galaxy Distribution

Cosmology Group at
Korea Astronomy and Space Science Institute



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XiaoDong Li
David Mota

IBS, DAEJEON - MAY - 2015

Outline

- Background
  - What do we want?
  - From observations to theory

- Model-independent estimates of cosmic observables
  - utilizing the Alcock-Paczynski effect
    - Clustering peaks (w/ YongSeon Song)
    - Clustering shells (w/ Changbom Park, XiaoDong Li)

- Test for Modified Gravity?
  - In redshift-space (w/ David Mota & Claudio Llinares)

Background

Key observables in spectroscopic galaxy surveys:

(1) Angular diameter distance $\mathbf{D_A}$
- Exploiting BAO as standard rulers which measure the angular diameter distance and expansion rate as a function of redshift.

(2) Radial distance $\mathbf{H^{-1}}$
- Exploiting redshift distortions as intrinsic anisotropy to decompose the radial distance represented by the inverse of Hubble rate as a function of redshift.

$$H(z) = H_0\sqrt{\Omega_m a^{-3} + (1-\Omega_m)a^{-3(1+w)}},$$

$$D_A(z) = \frac{1}{1+z} r(z) = \frac{1}{1+z}\int_0^z \frac{dz'}{H(z')},$$

(3) Growth Rate, f **(dδ/d ln a)**
- The coherent motion, or flow, of galaxies can be statistically estimated from their effect on the clustering measurements of large redshift surveys, or through the measurement of redshift space distortions.

These are essential to test theoretical models explaining cosmic acceleration; **ΛCDM, Dynamical DE, Einstein's gravity**

From Observation to theory

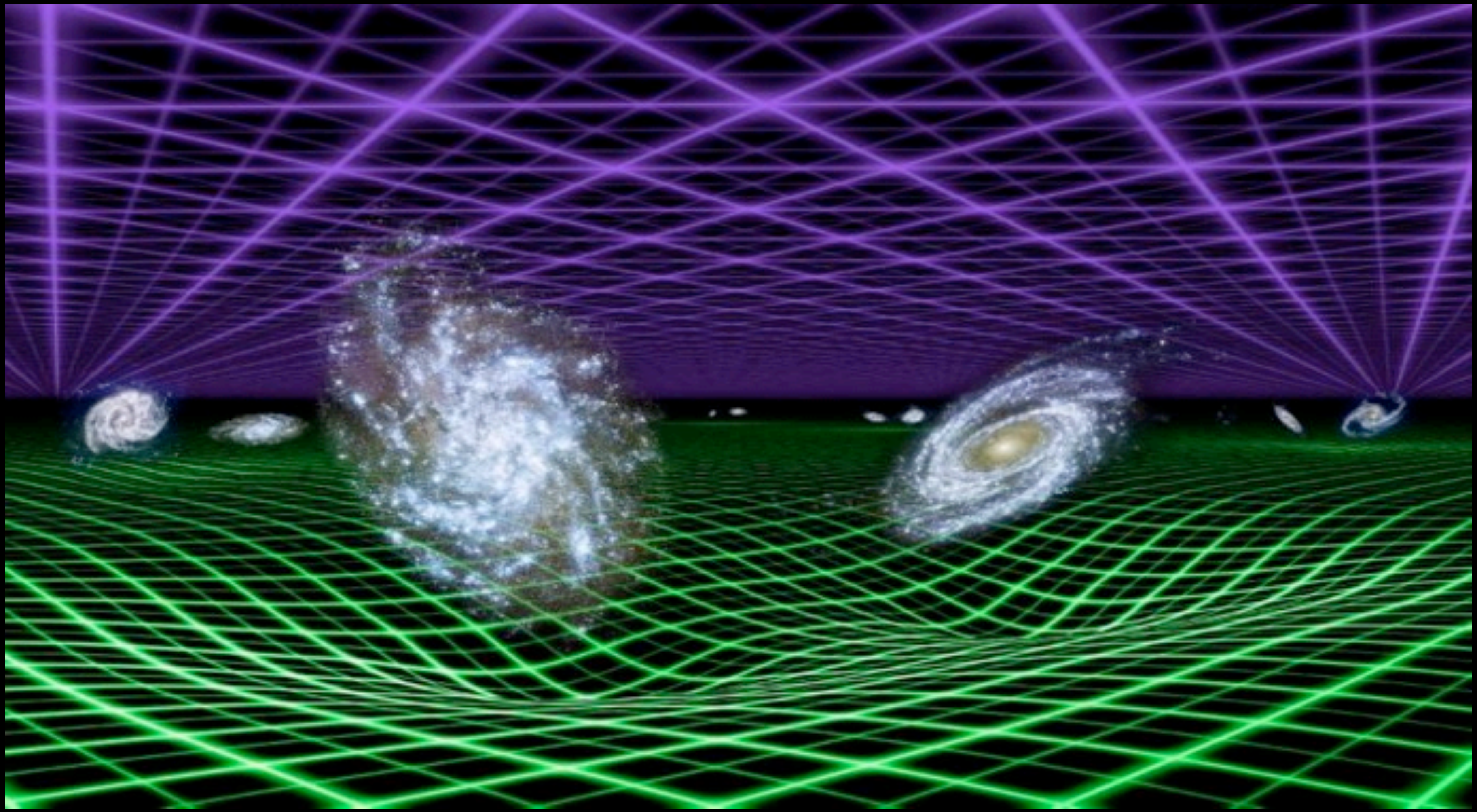
- We want to know the density perturbations in the universe (at various cosmic times). This will tell us about the cosmic expansion (a) and gravity, through the growth of structure.

We don't 'see' perturbations of the total density field.
We observe individual galaxies that trace that underlying matter distribution.

How are galaxies and DM related?

- Halo Model
- Bias
  - Scale Dependent?

- Velocity Field Bias?



From Observation to theory

- We want to know the density perturbations in the universe (at various cosmic times). This will tell us about the cosmic expansion (a) and gravity, through the growth of structure.

Also....

We don't 'see' the true radial position of galaxies
We see its redshift, which is composed of a hubble expansion and a peculiar velocity due to local gravitational dynamics.

Furthermore, even if the galaxy is not moving gravitationally, we still do not know its true position in comoving space, since we need to transform (theta, phi, redshift) -> (x,y,z) using a cosmological model with a specific choice of parameters. Eg LCDM Om=0.3, Ol=0.7, w=-1 etc etc

We also don't see the galaxy's true angular position on the sky due to gravitational lensing, but let's leave that for another talk.

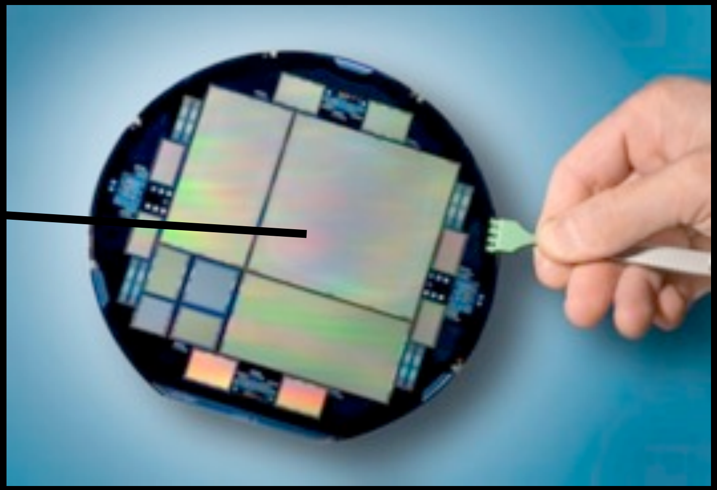
So, where do we go from here?

The Data: Baryon Oscillation Spectroscopic Survey (BOSS)

- Straightforward upgrades to be commissioned in summer 2009

SDSS telescope + most systems unchanged

1000 small-core fibers to replace existing (more objects, less sky contamination)



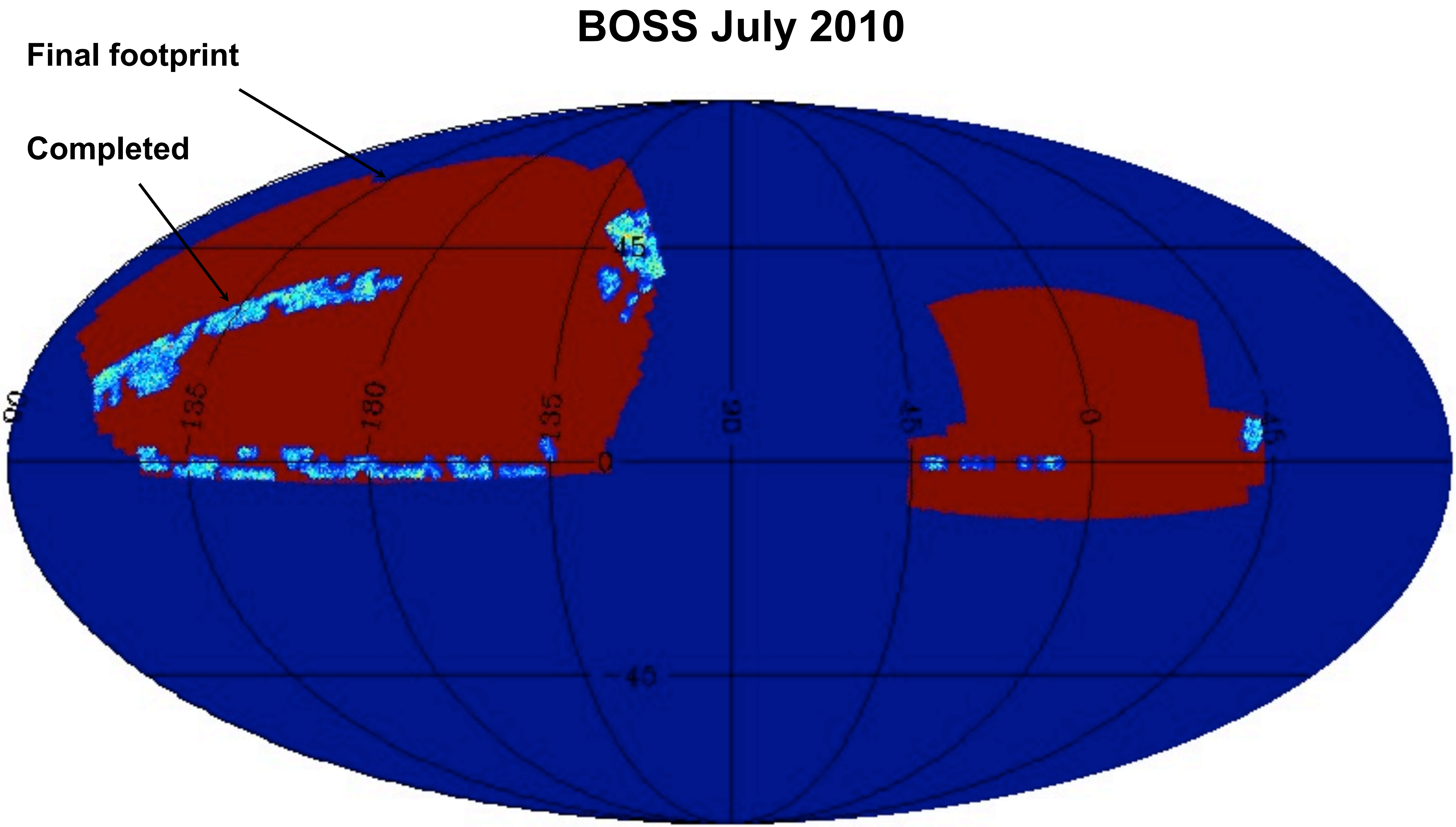
LBNL CCDs + new gratings improve throughput
Update electronics + DAQ

Apache Point Observatory (SDSS 2.5m telescope)

Photometry in standard UGRIZ bands

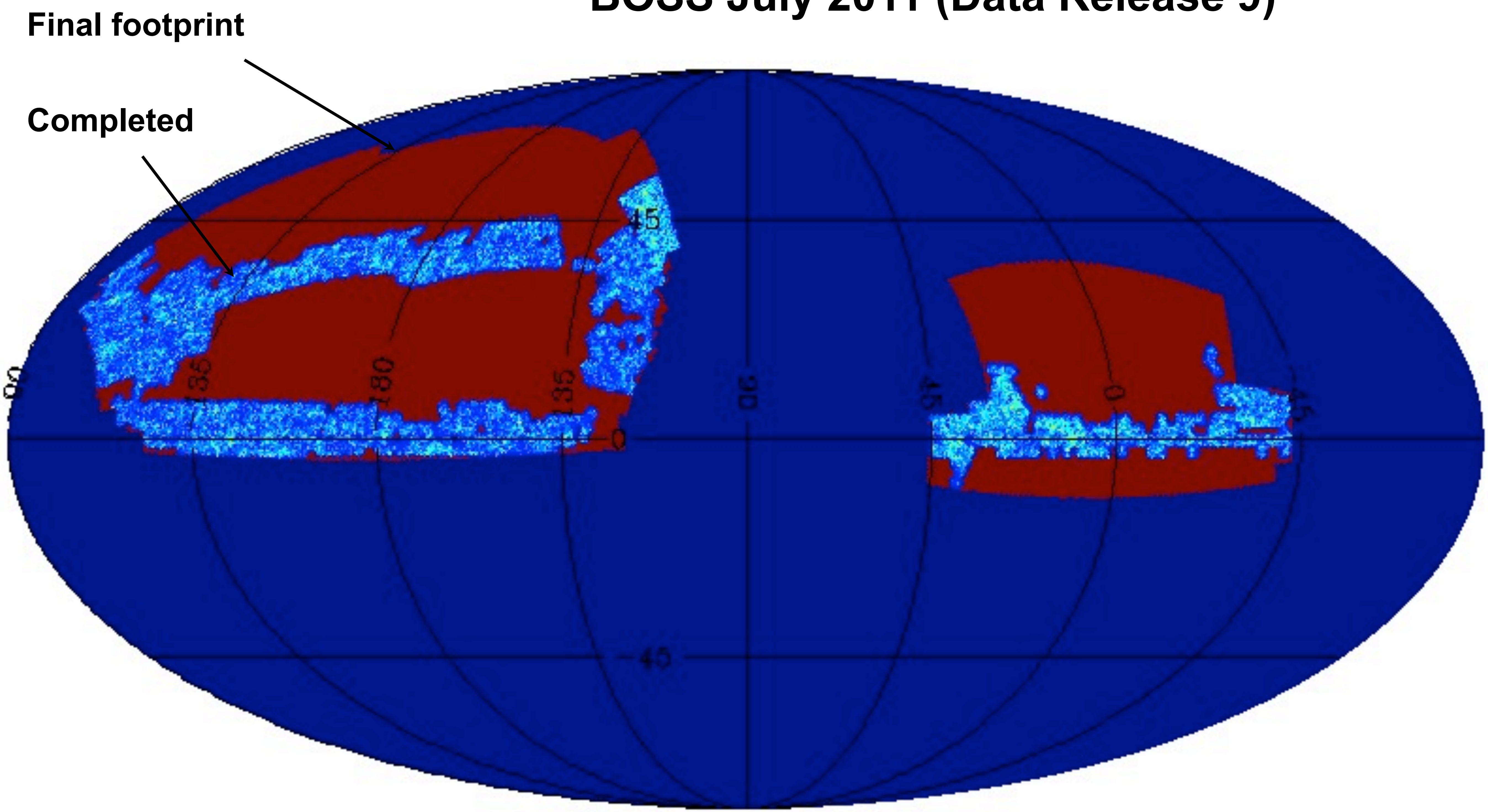
Imaging with 30 2048 × 2048 SITe/Tektronix 49.2 mm square CCDs on a field of view 2.5 deg operating in drift scan mode.

BOSS: Survey Progress



BOSS: Survey Progress

BOSS July 2011 (Data Release 9)

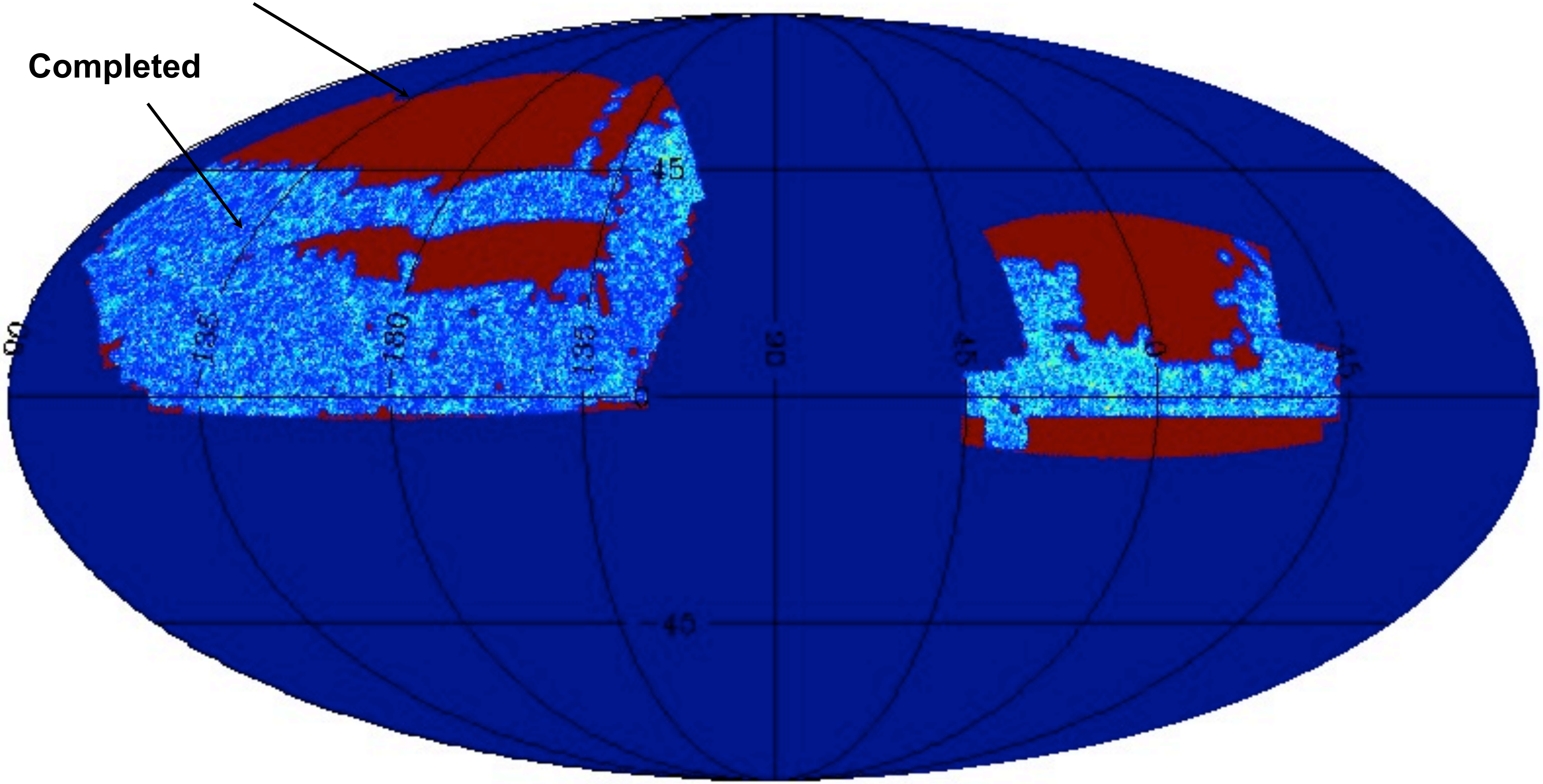


BOSS: Survey Progress

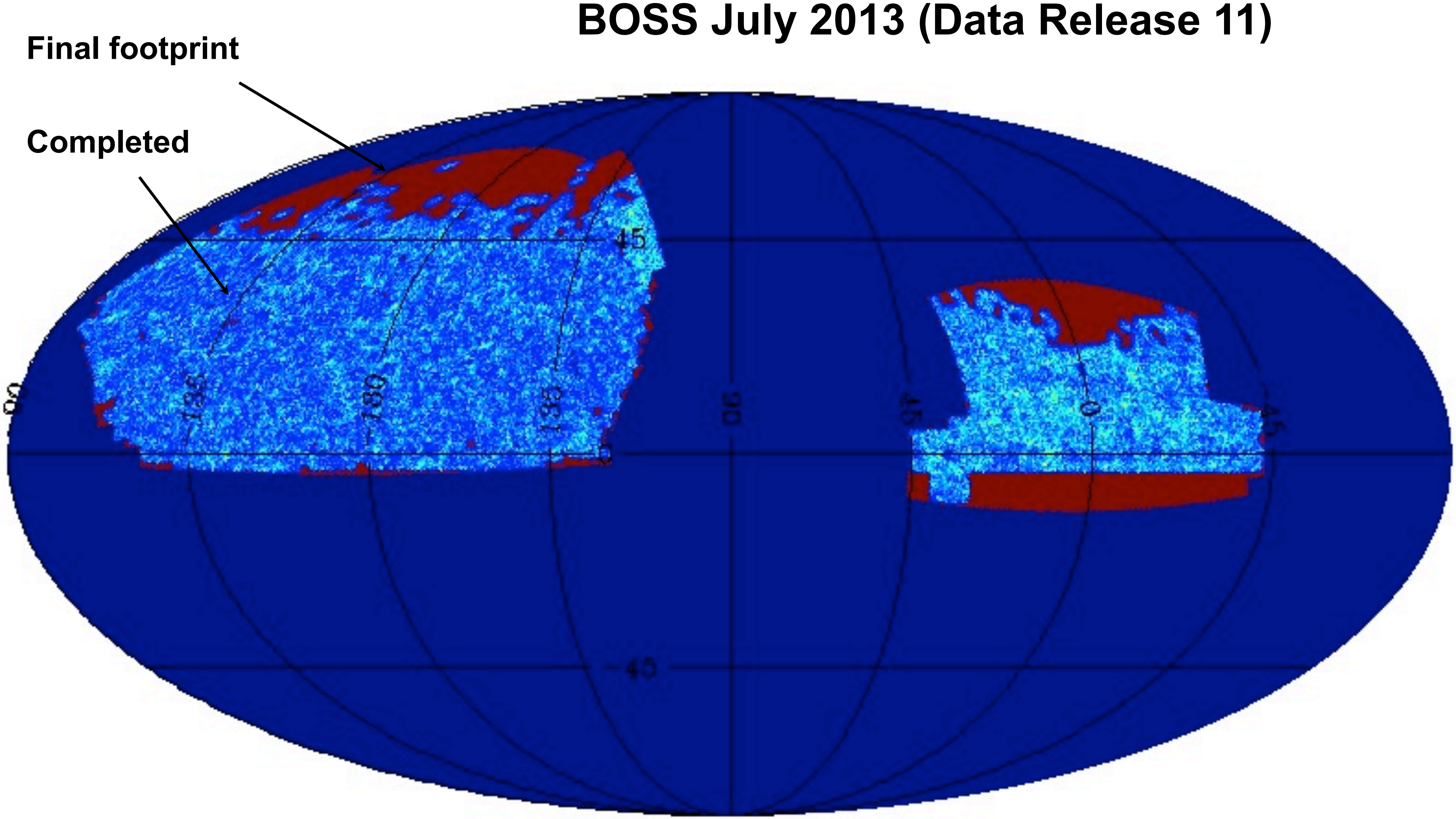
BOSS July 2012 (Data Release 10)

Final footprint

Completed



BOSS: Survey Progress



Galaxy redshift success rate 97% (requirement was >=94%)

Correlation Functions

We want to evaluate:
where δ is the density contrast

$$\langle \delta(x)\delta(x+r) \rangle$$

We call this the Two Point Correlation Function (2PCF)

$$\xi_i(r) = \frac{n_i(r)}{\bar{n}.dV} - 1$$

The estimator for this statistic is:

$$\xi(r) = \frac{DD - 2DR + RR}{RR}$$

This lead to the probability:

$$dP = n^2[1+\xi(r)]dV_1 dV_2$$

Correlation Functions

We want to evaluate: $\langle\delta(x)\delta(x+r)\rangle$
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We call this the Tv
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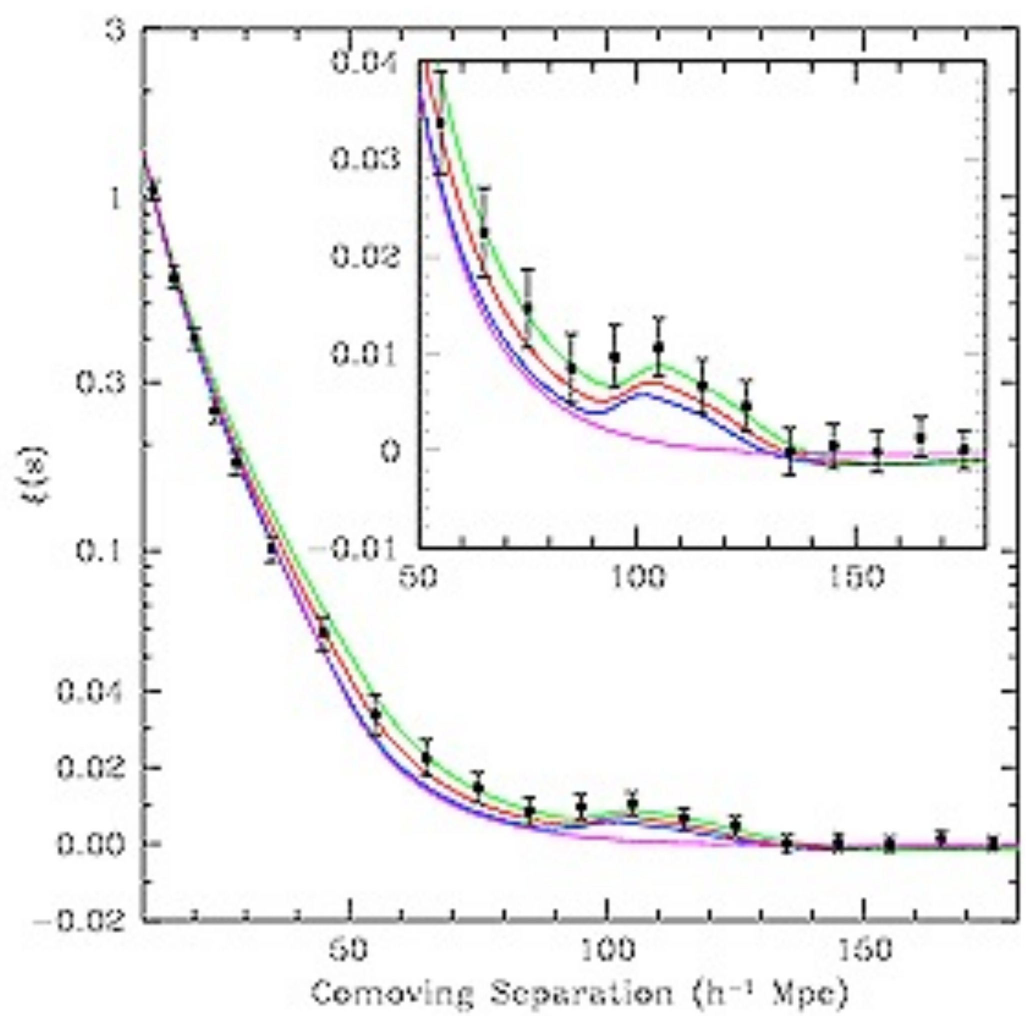

(www.sdss3.org)

The estimator for
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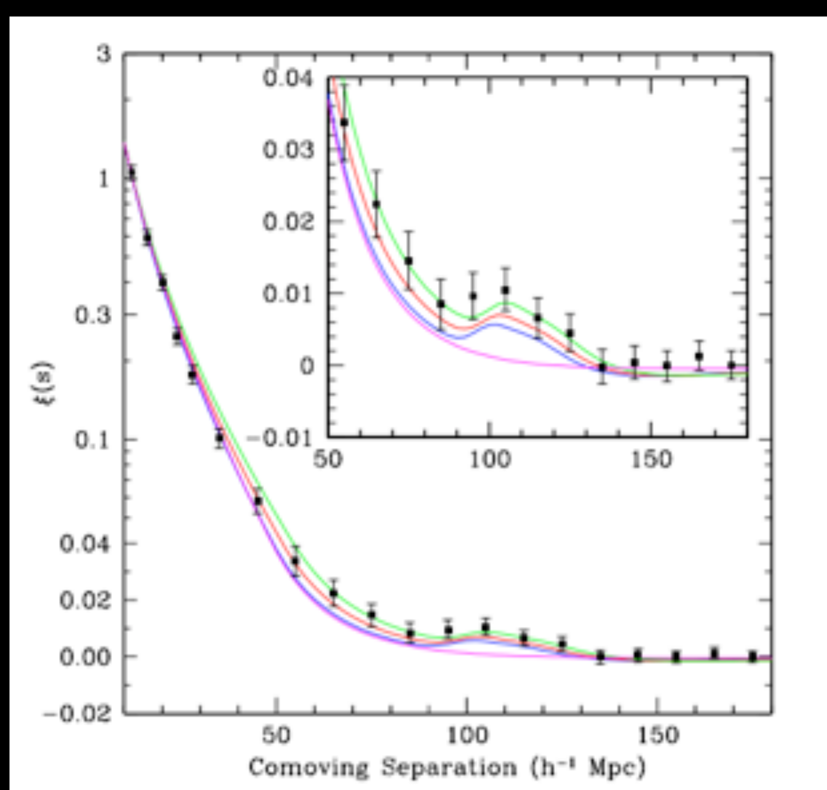
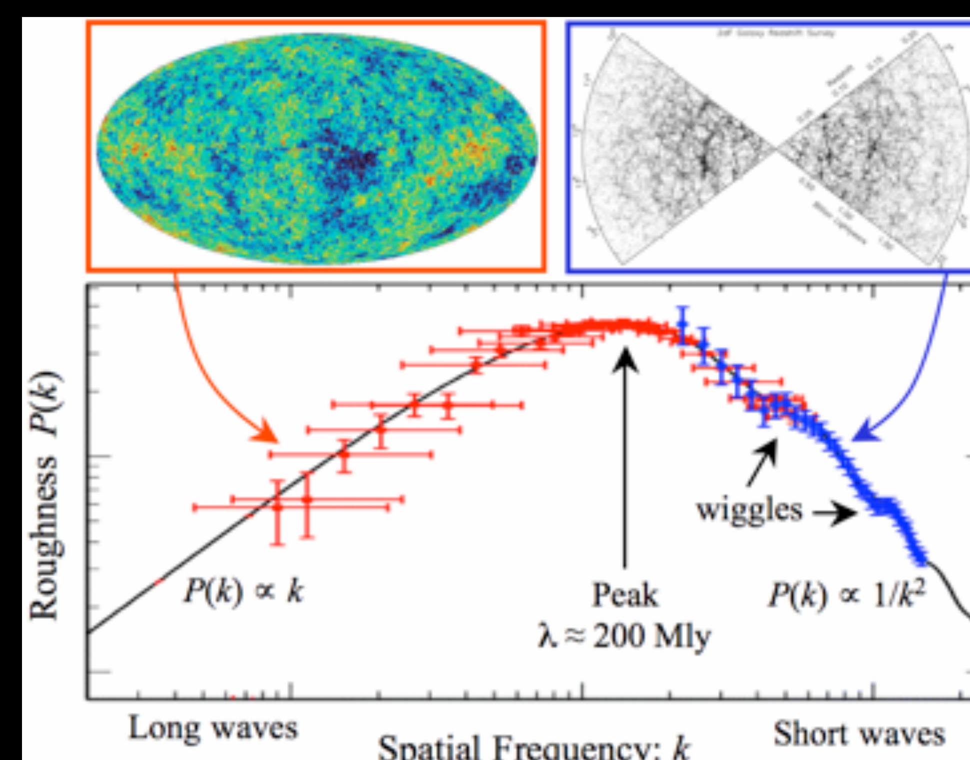
This lead to the probability: $dP = n^2[1+\xi(r)]dV_1 dV_2$

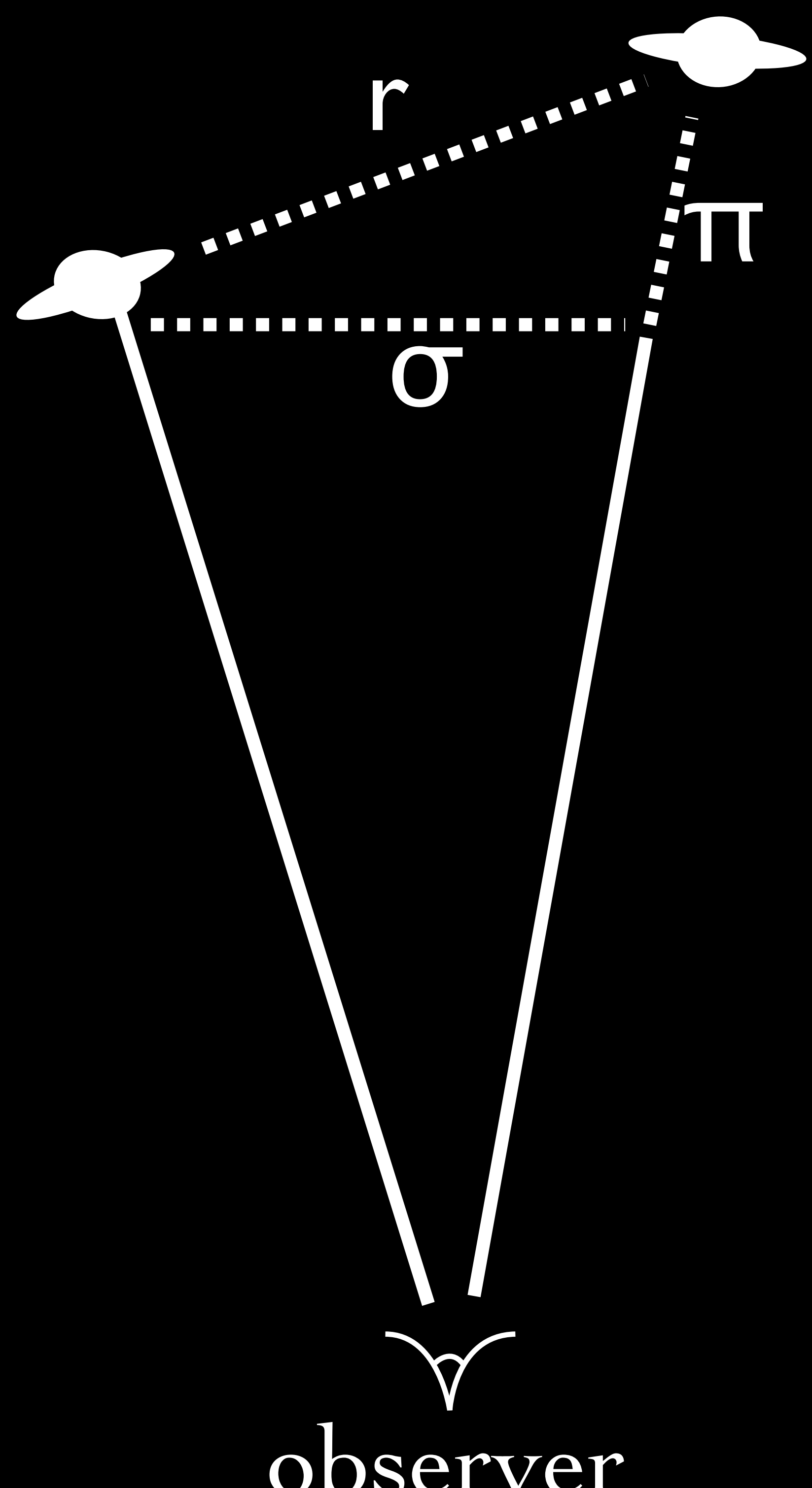
- I will present everything in terms of correlation statistics because they are easier to compute on real data
- However... Correlation functions and Power Spectra are informationally equivalent
- Xi(r) <~> P(k)





Anisotropic 2PCF

From 1D to 2D



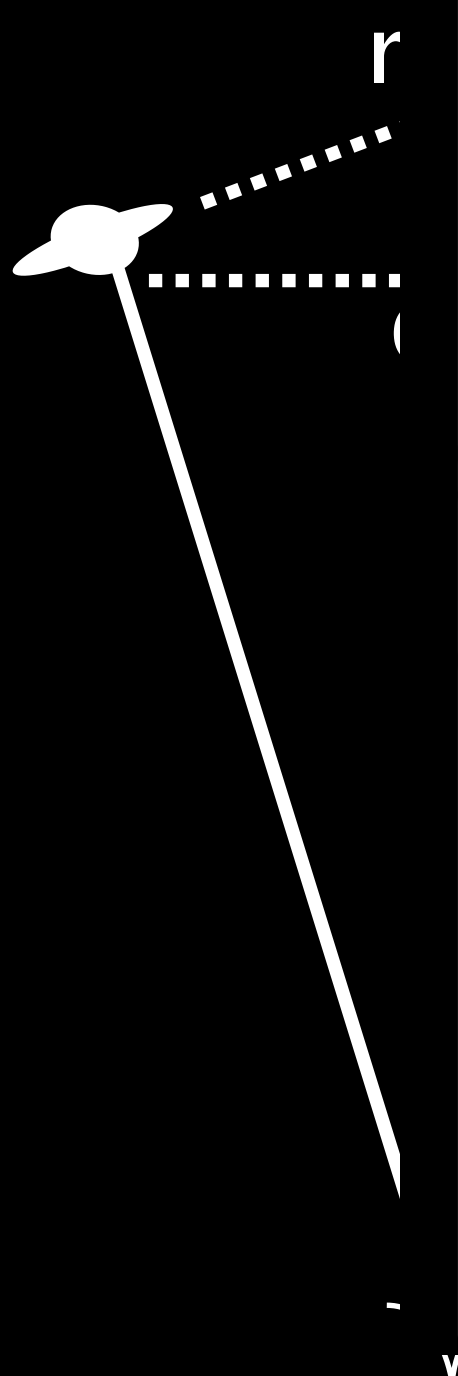
Bin galaxy pairs in two distances (π,σ) instead of the single distance between pairs, r.

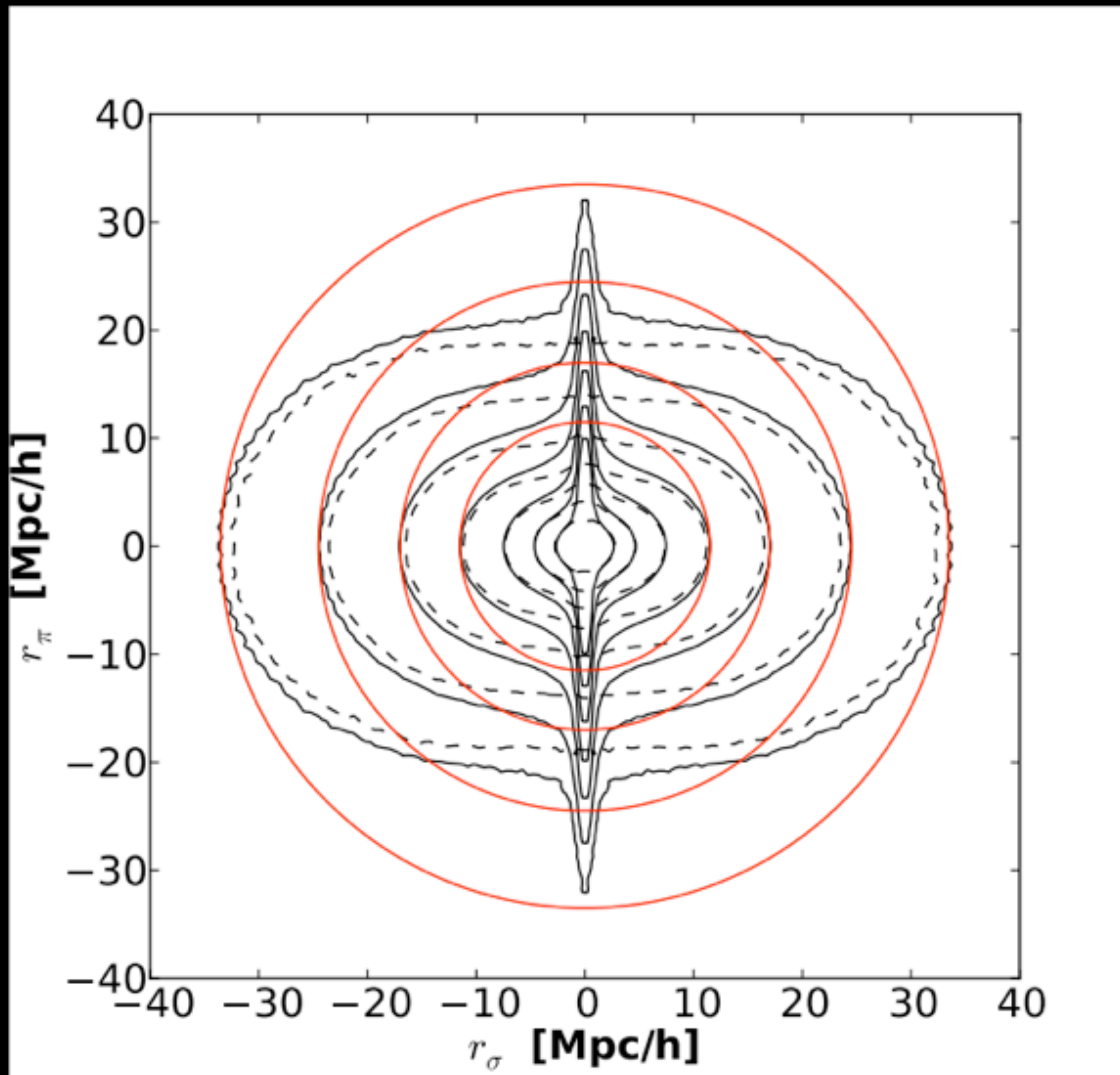
Apart from the binning this is the same as doing the 2PCF.

And if there are no preferred directions then the correlation function will give perfectly circular contours in (π,σ).

$$\xi(r) = \frac{DD - 2DR + RR}{RR}$$

Anisotropic 2PCF





nces (π,σ)
between

s the same

directions
will give
(π,σ).

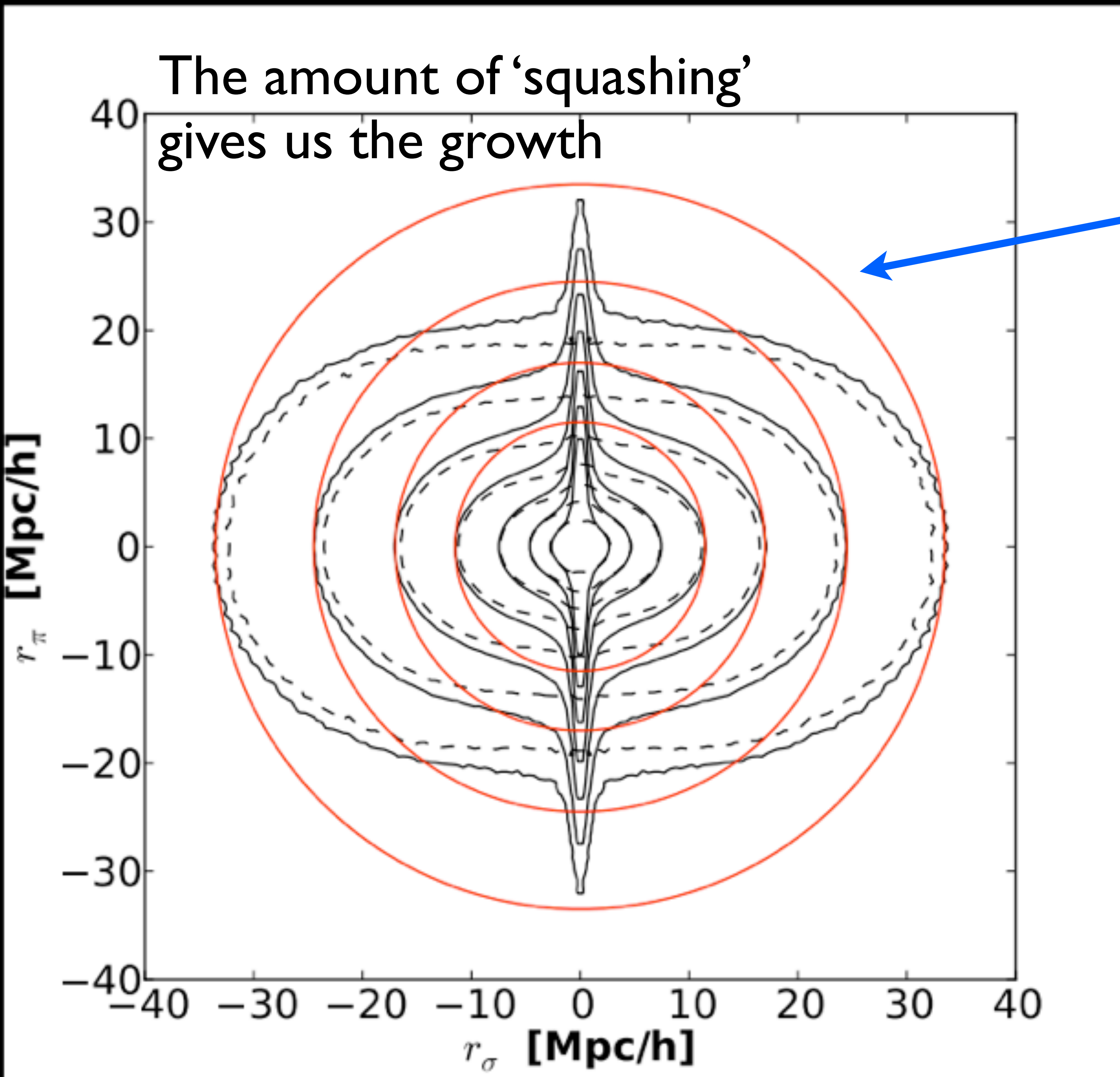
RR

Anisotropic 2PCF

3 contributions to anisotropic clustering:

- Non-linear, Fingers of God (FoG)
- Linear, Large Scale Velocities (Kaiser)
- Incorrect cosmological parameters
  - Alcock-Paczynski effect (AP)

Anisotropic 2PCF



Red - No RSD

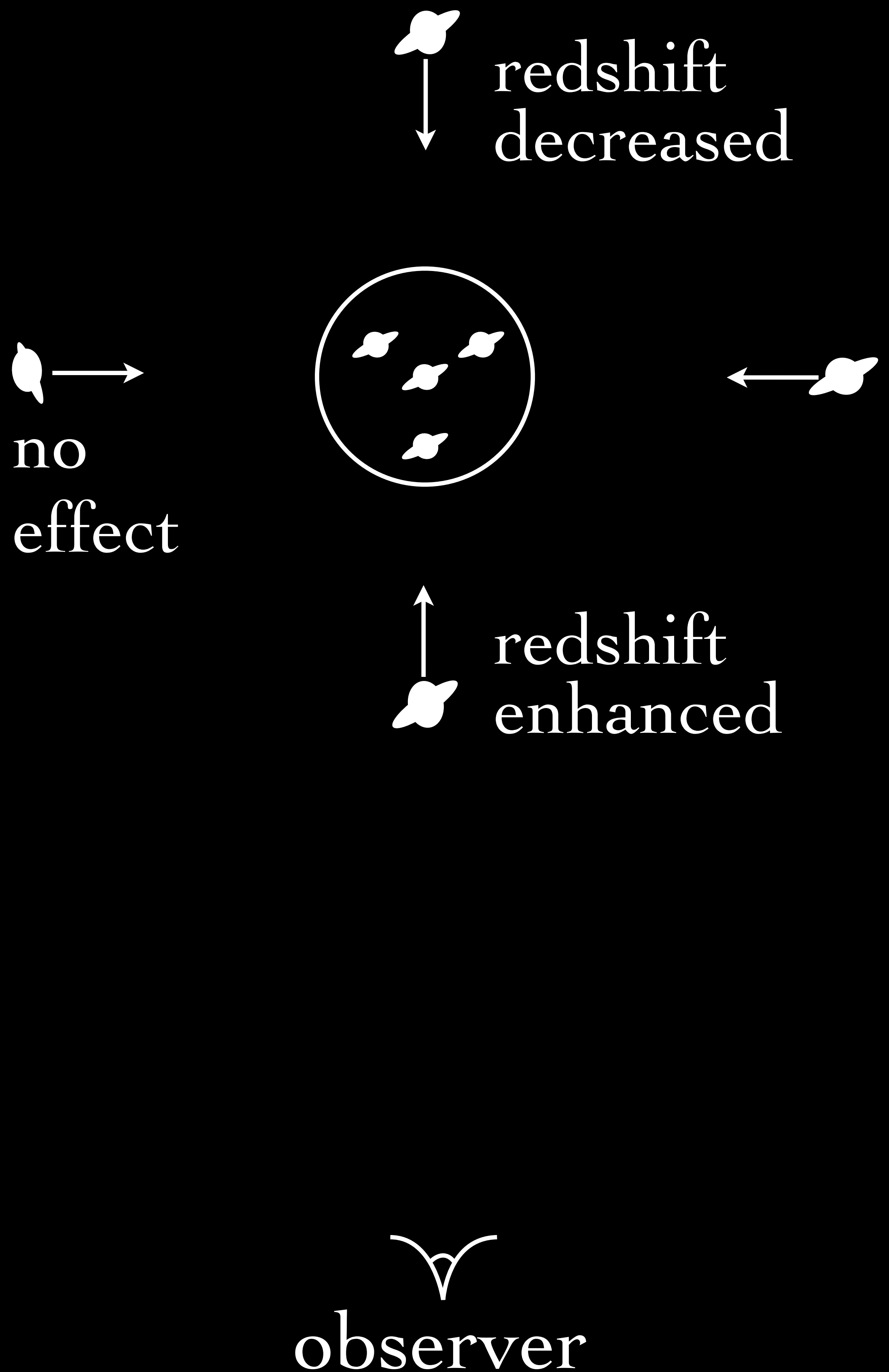
Dashed - Linear

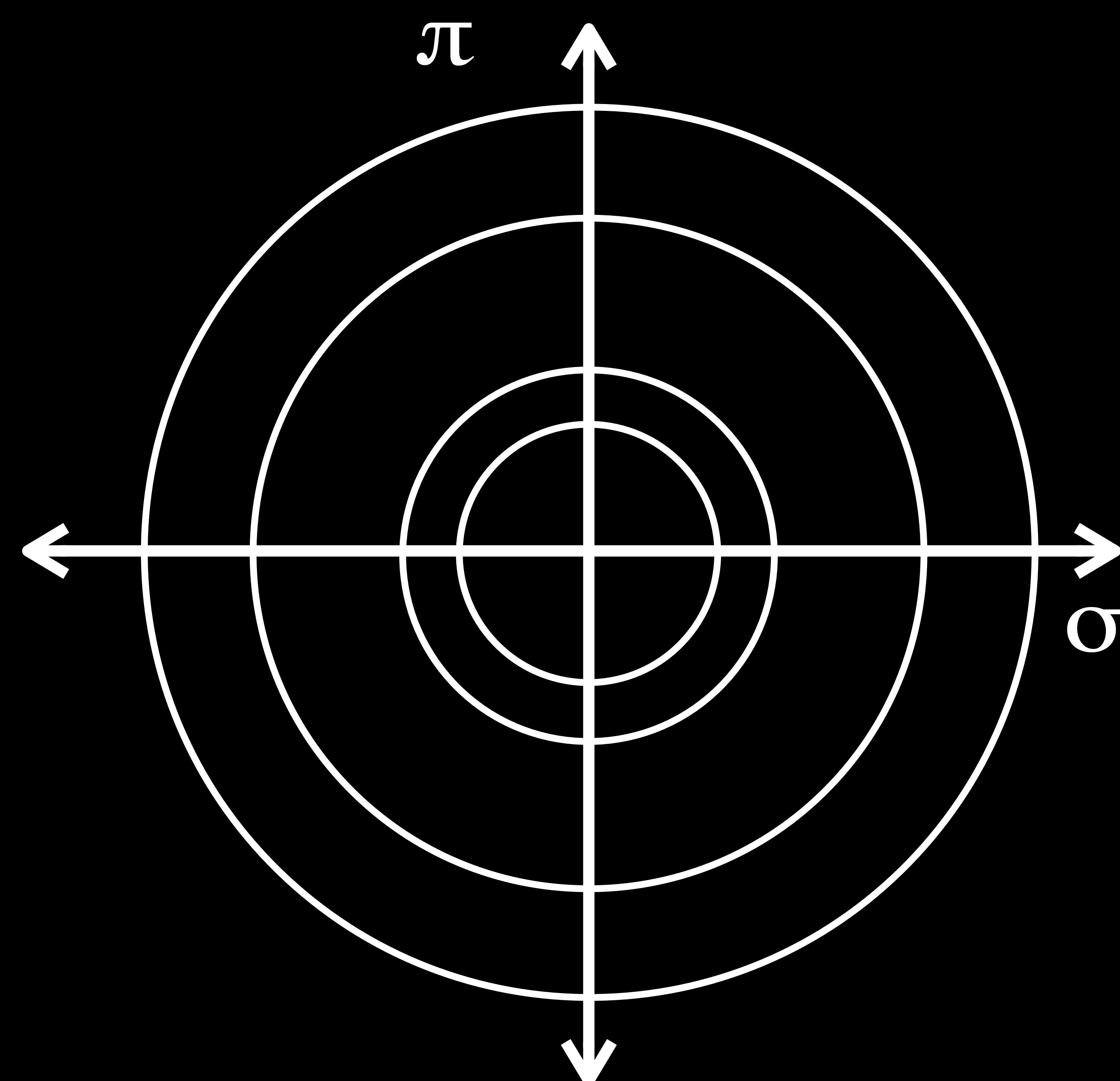
Solid - Linear + FoG

Nonlinear regime theoretically difficult to model

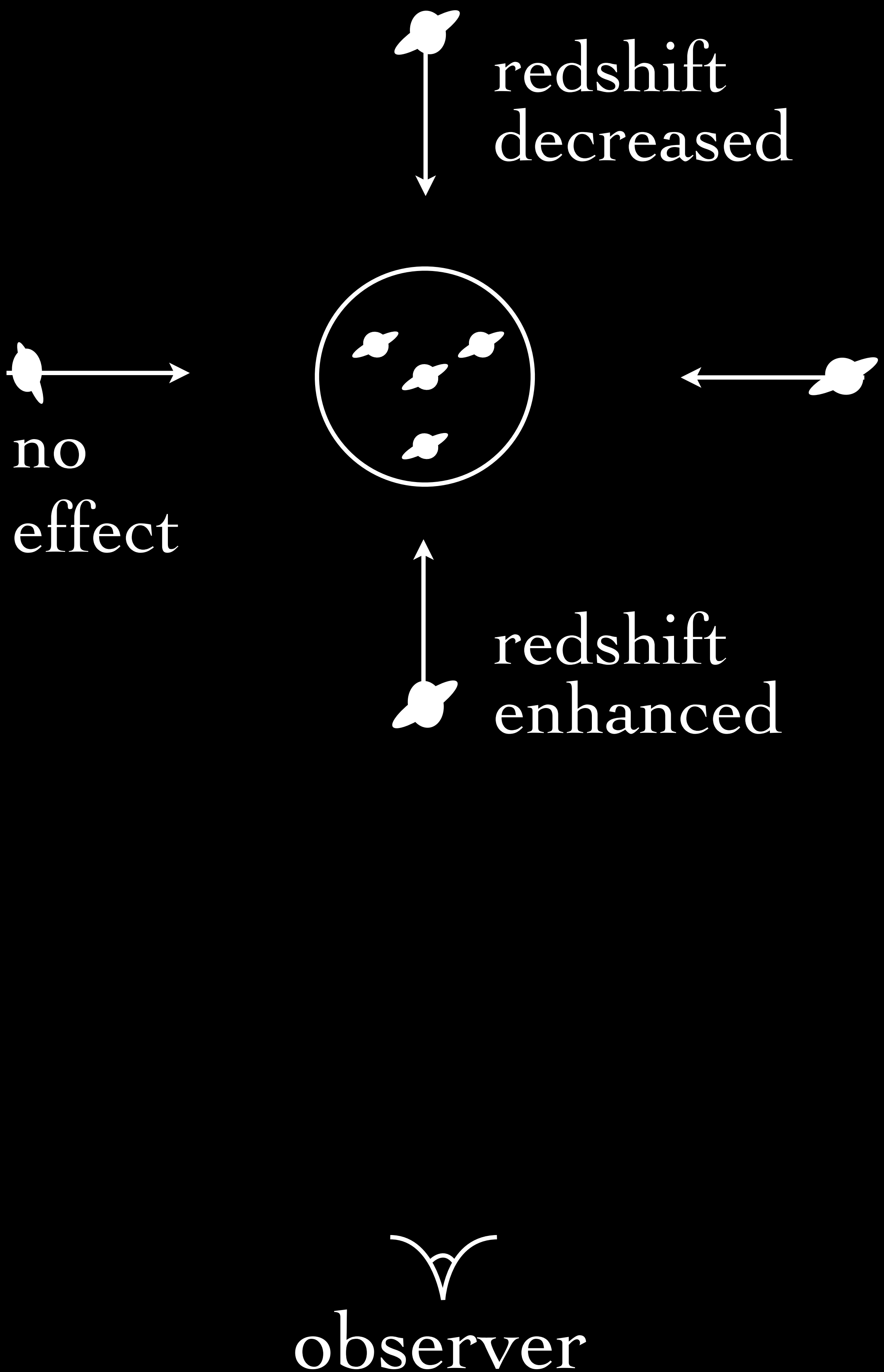
M. White et al (2011)

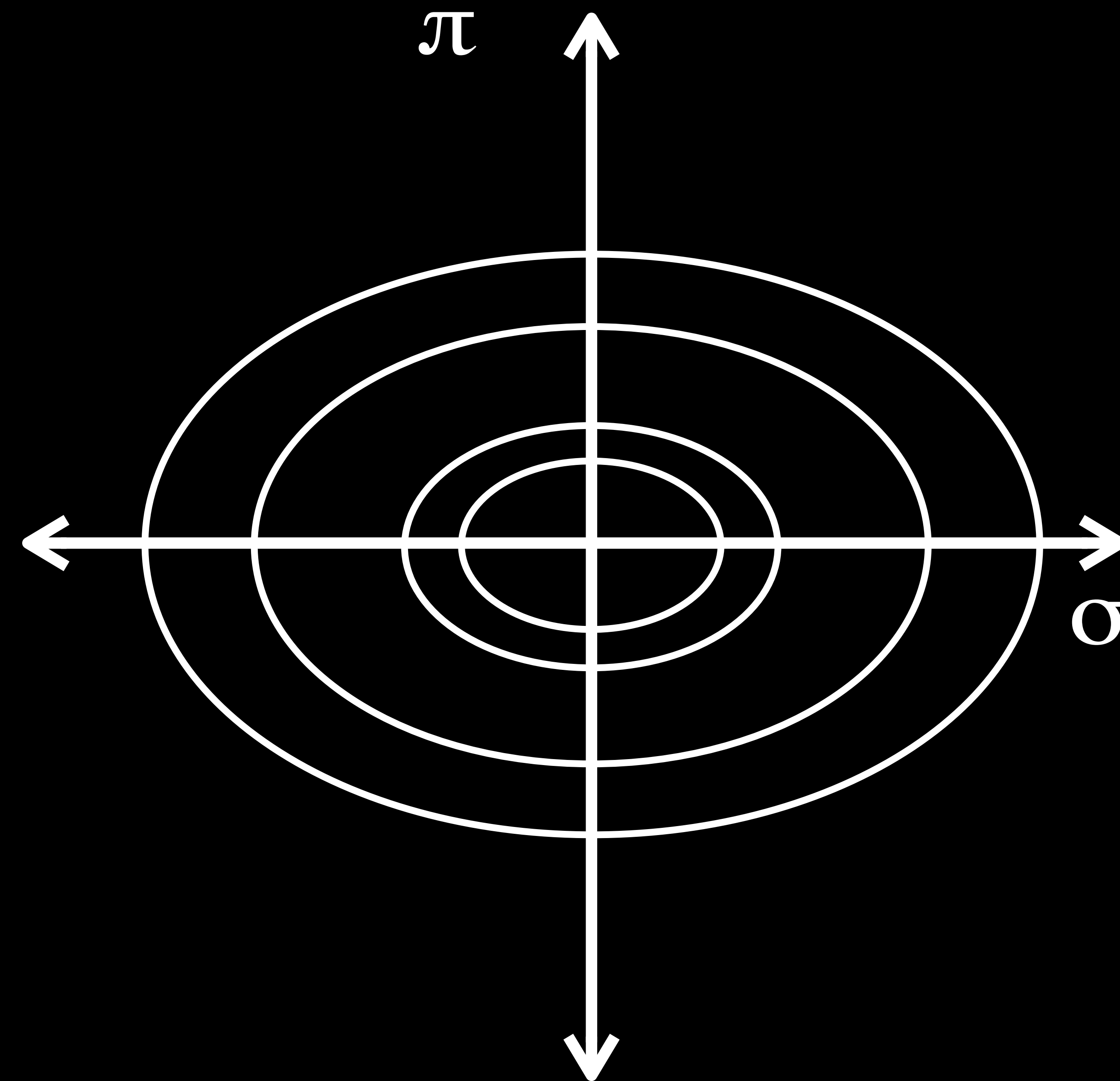
Kaiser Effect





Kaiser Effect

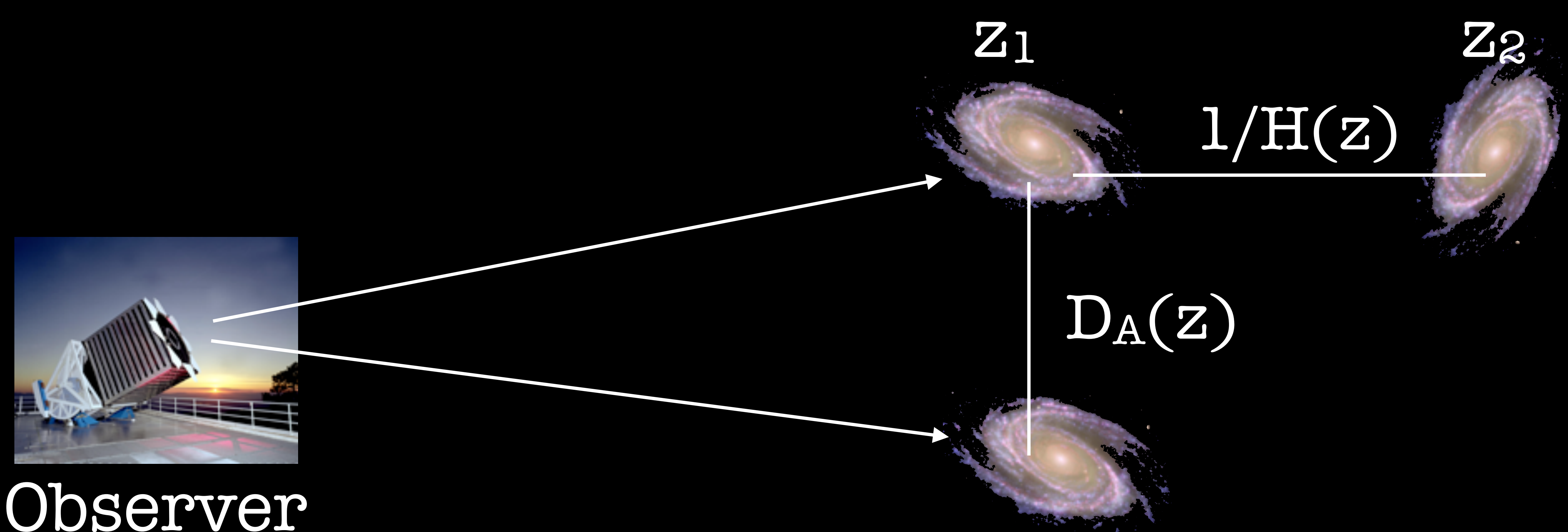




Alcock-Paczynski Effect

We measure RA, Dec and Redshift for each galaxy. However we must choose a cosmological model to convert these positions into a cartesian comoving coordinate system.

Even without a standard ruler, we can measure the clustering along and perpendicular to the line of sight and thus constrain the combination of $D_A * H$



Alcock-Paczynski Effect

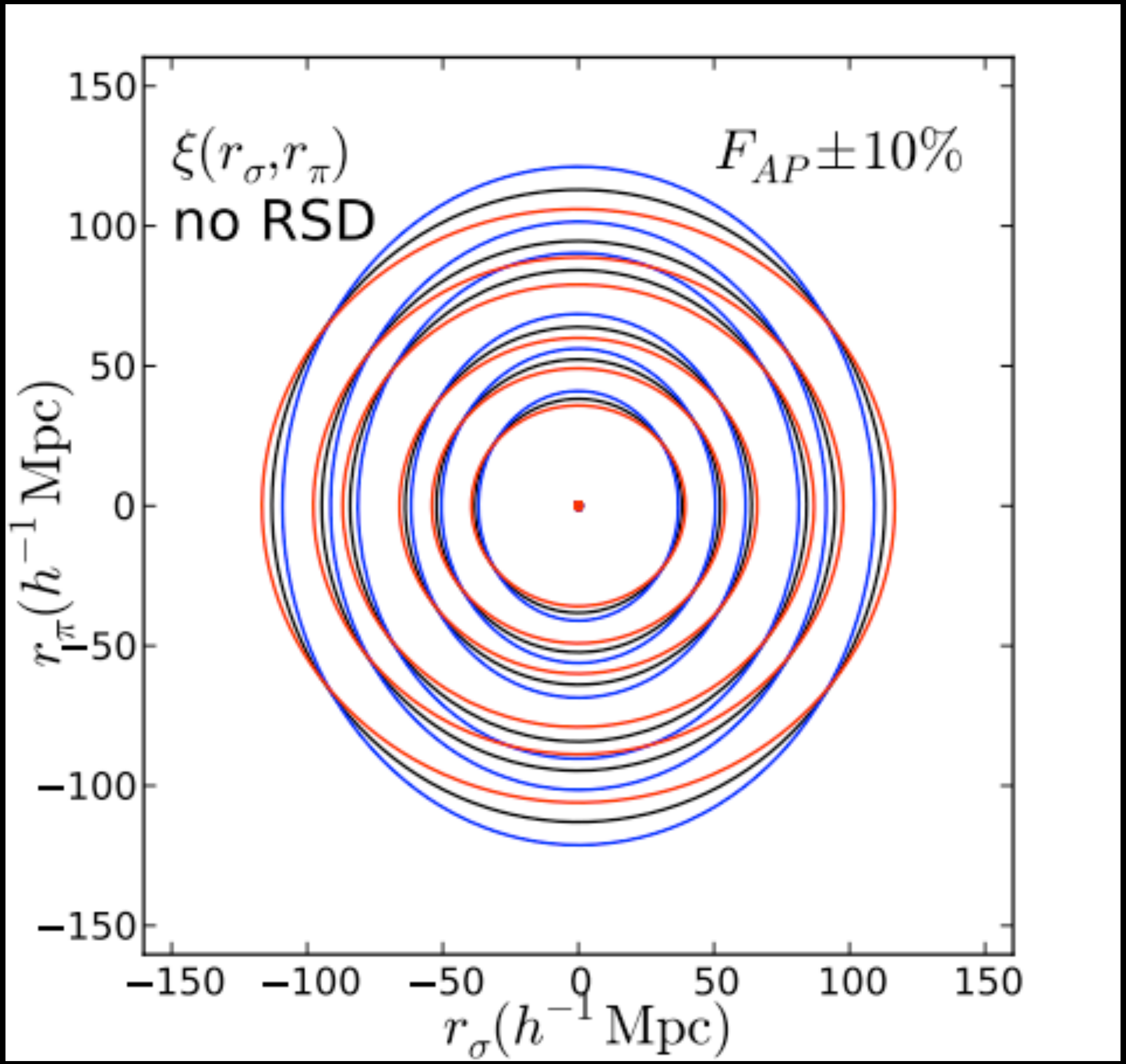
$\xi(r_p, \pi)$ appears anisotropic if you assume the wrong cosmology;

constrains the combination:
$F(z) \equiv (1+z)\, D_A(z)\, H(z)/c$

However geometric distortions can be modeled exactly:

$$\xi^{\rm fid}(r_\sigma, r_\pi) = \xi^{\rm true}(\alpha_\perp r_\sigma, \alpha_\parallel r_\pi),$$

$$\alpha_\perp = \frac{D_A^{\rm fid}(z_{\rm eff})}{D_A^{\rm true}(z_{\rm eff})}, \qquad \alpha_\parallel = \frac{H^{\rm true}(z_{\rm eff})}{H^{\rm fid}(z_{\rm eff})},$$



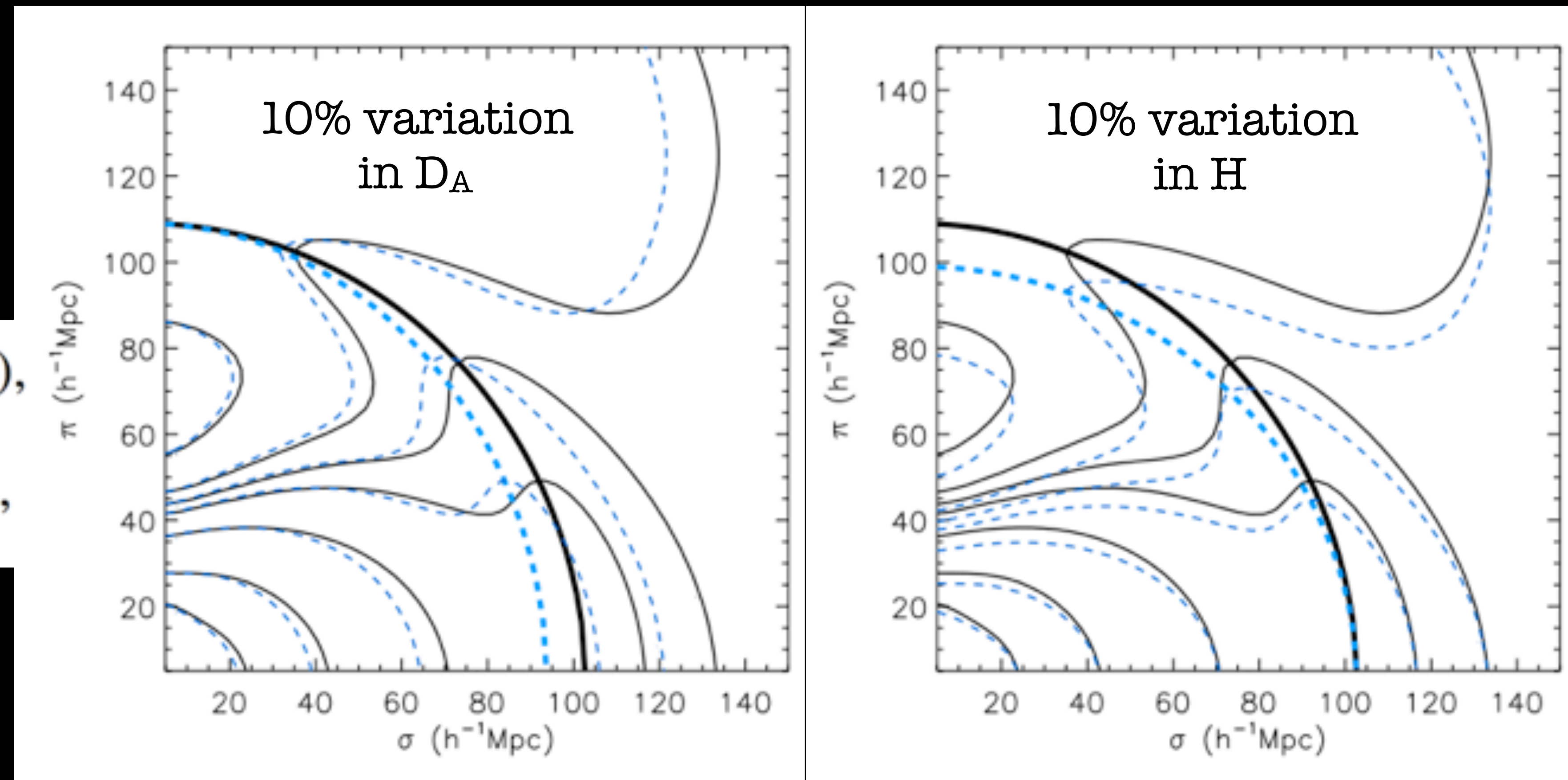
Clean Alcock-Paczynski Measure

Theoretically the geometric distortions of the AP effect can be modeled exactly:

$$\xi^{\rm fid}(r_\sigma, r_\pi) = \xi^{\rm true}(\alpha_\perp r_\sigma, \alpha_\parallel r_\pi),$$

$$\alpha_\perp = \frac{D_A^{\rm fid}(z_{\rm eff})}{D_A^{\rm true}(z_{\rm eff})}, \qquad \alpha_\parallel = \frac{H^{\rm true}(z_{\rm eff})}{H^{\rm fid}(z_{\rm eff})},$$

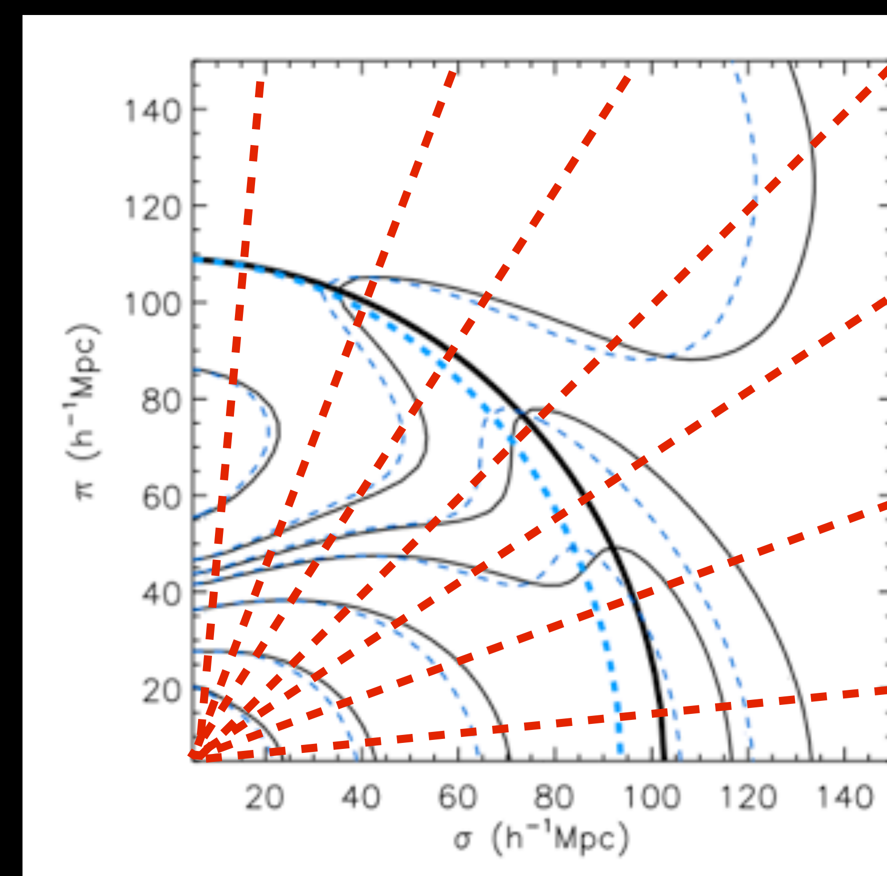
D_A, H vary peak positions off the BAO ring.



We want to avoid fitting the full shape of the anisotropic correlation function, as it depends on unknown systematic and physics, like scale dependent bias, etc.

A cleaner method would be to just measure the shape of the BAO ring.

We can do this by looking at many thin wedges in this 2D projection, i.e. many directionally constrained 1-D correlation functions.

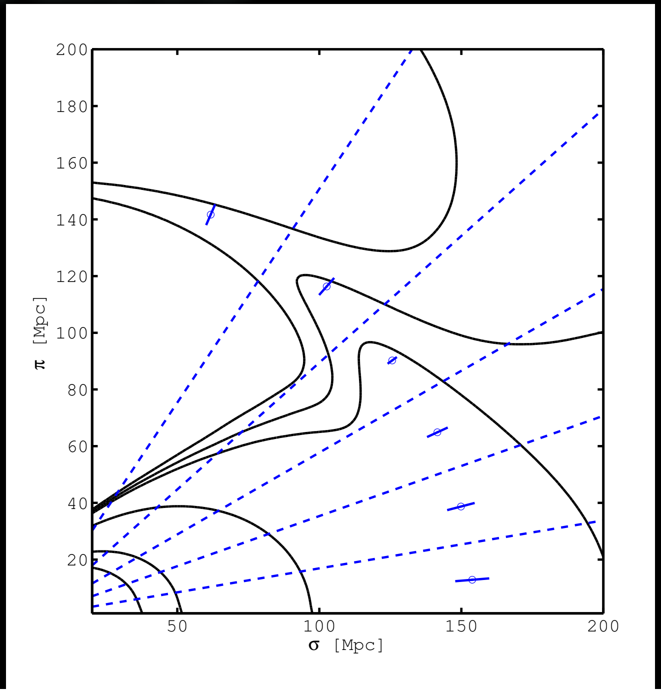


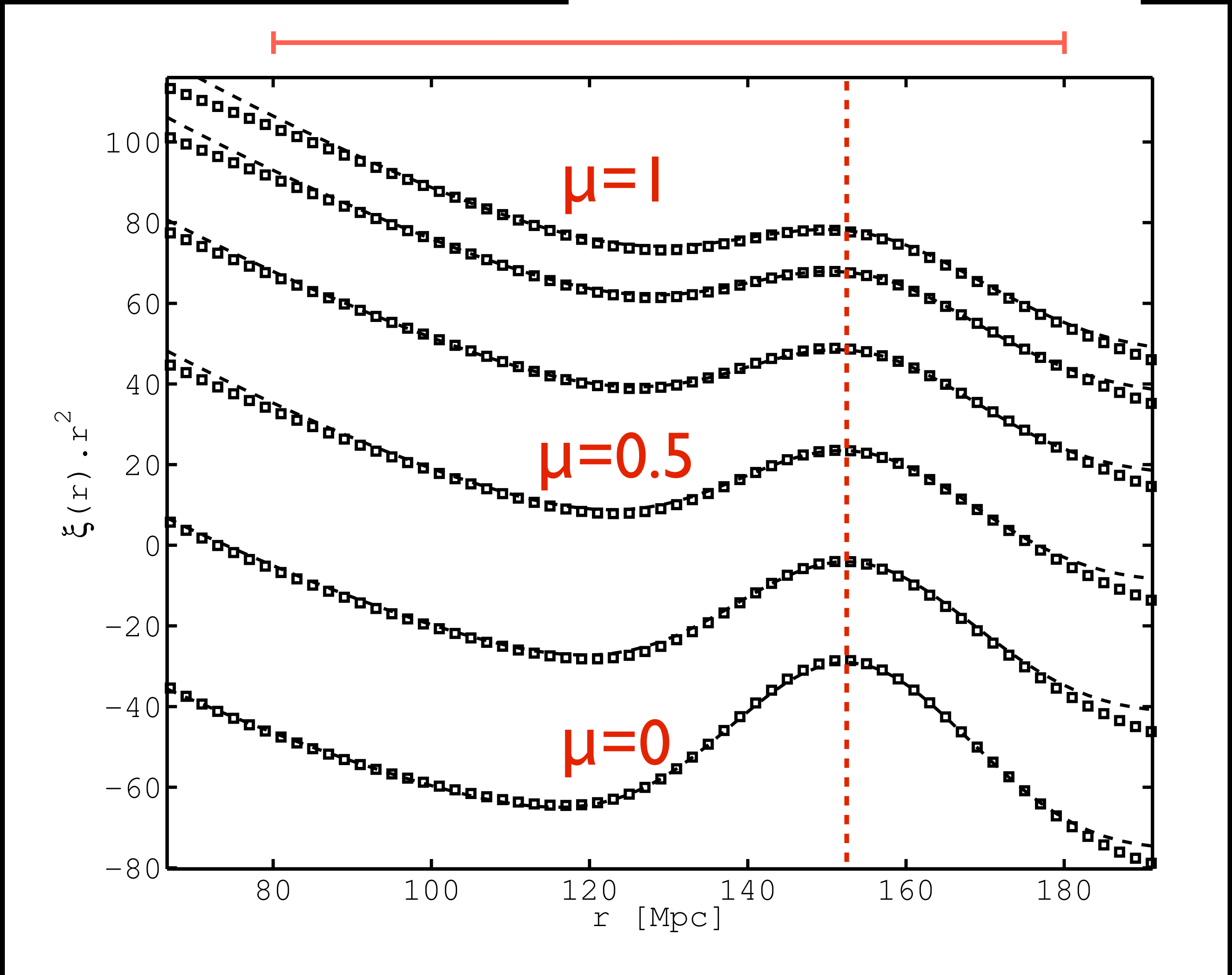
Anisotropic BAO Peaks

$$\xi_\mu(s) \times s^2 = A.s^2 + B.s + Ee^{-(s-D)^2/C} + F,$$

A simple function to approximate the shape of the correlation function
We use a quadratic plus a gaussian, fitted over the range 80<r<180 Mpc

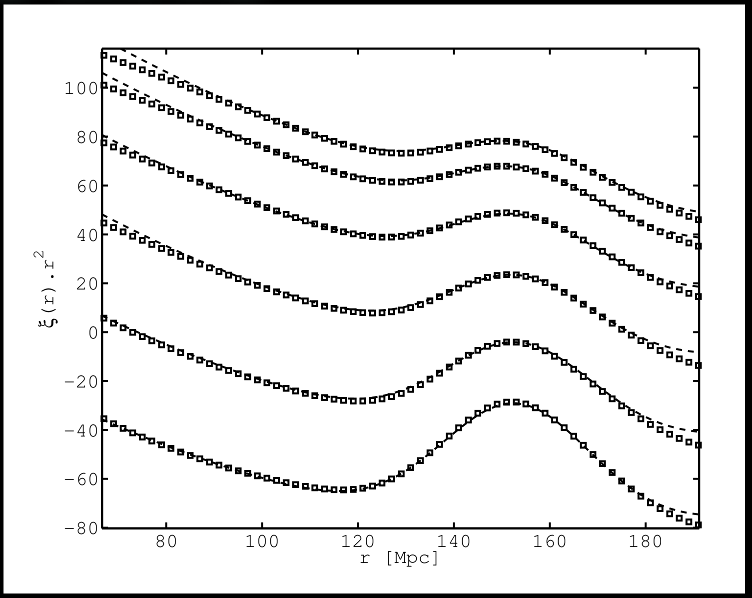
We care only about locating the BAO peak position. The centre of the gaussian is controlled by D.



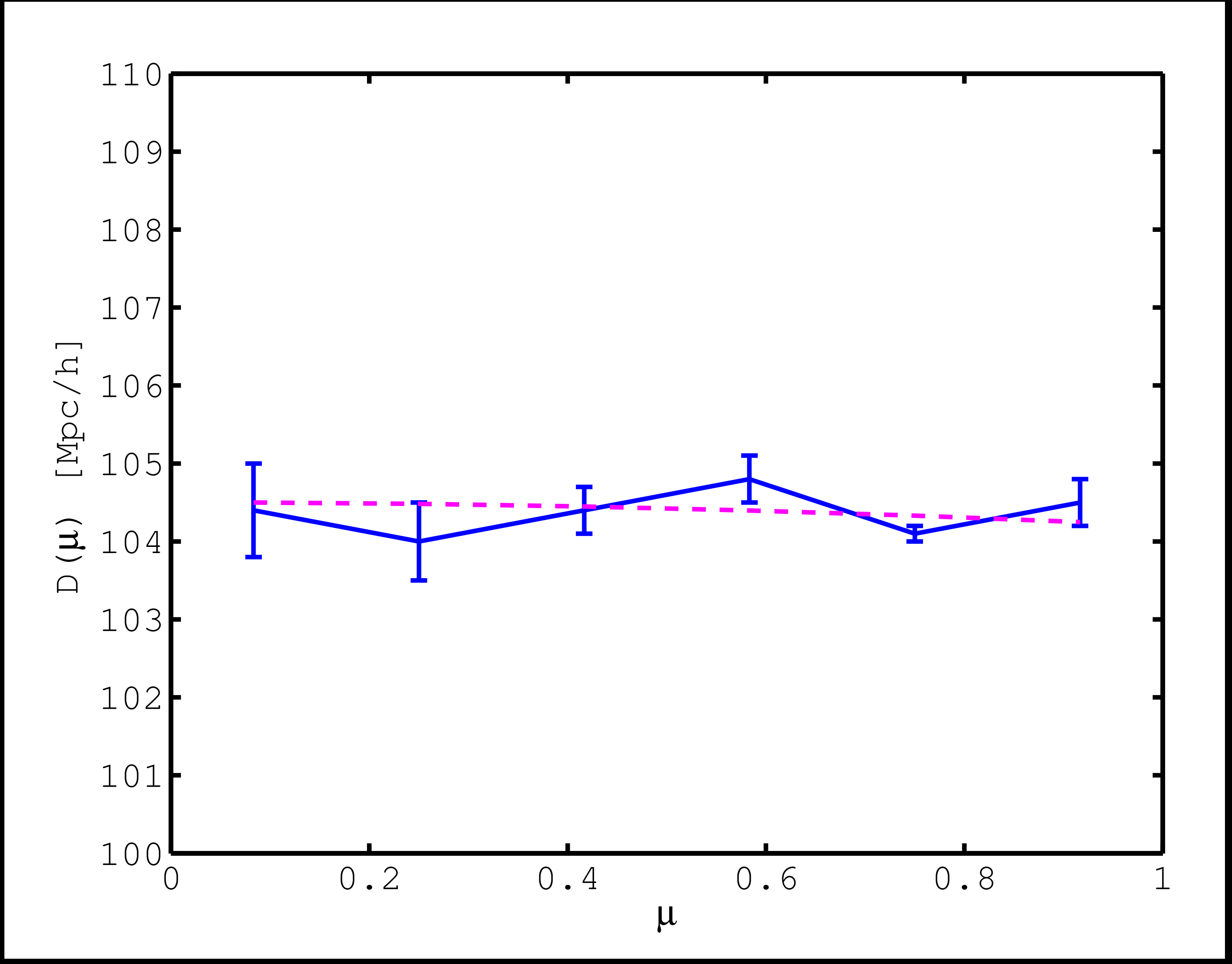


Anisotropic BAO Peaks

Simply we can fit an elliptic function to the obtained D(μ) and get a semi-major and minor distance defining an ellipse.



$$D(\theta) = \frac{D_{||} D_{\perp}}{\sqrt{(D_{||}\cos\theta)^2 + (D_{\perp}\sin\theta)^2}}$$



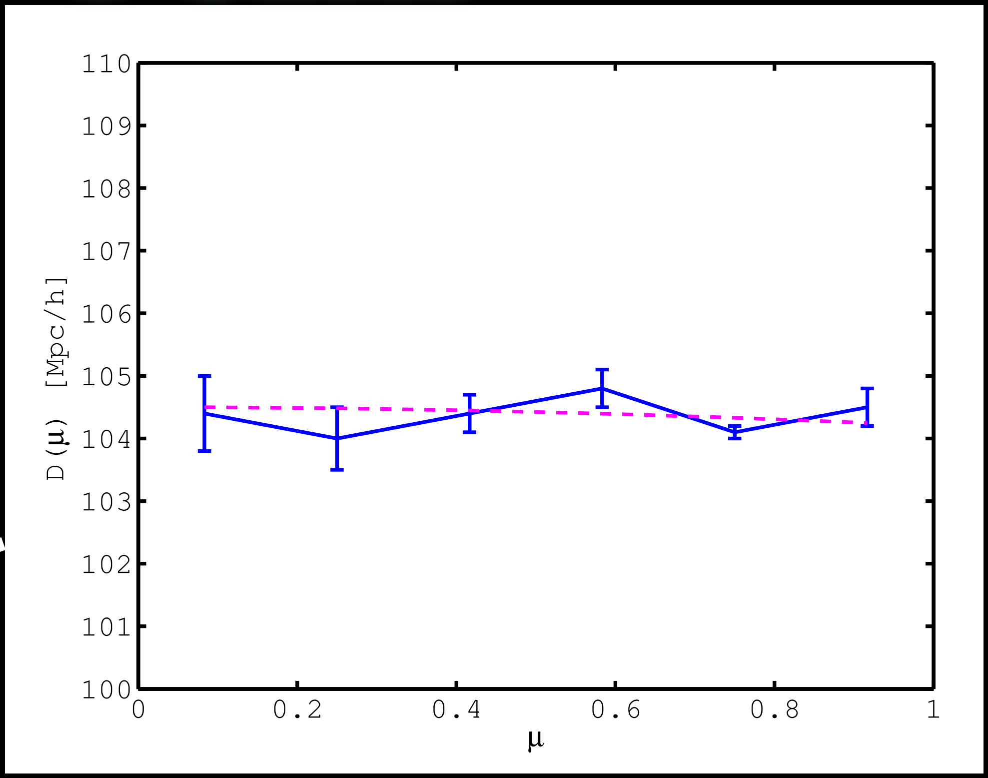
From this we constrain the two distances, $D_{//}$ along the line of sight and $D_{\perp}$ across the line of sight.

Anisotropic BAO Peaks

$$D(\mu) = \frac{D_{\perp}.D_{||}}{\sqrt{(D_{\perp}.\mu)^2 + D_{||}^2(1-\mu^2)}}$$

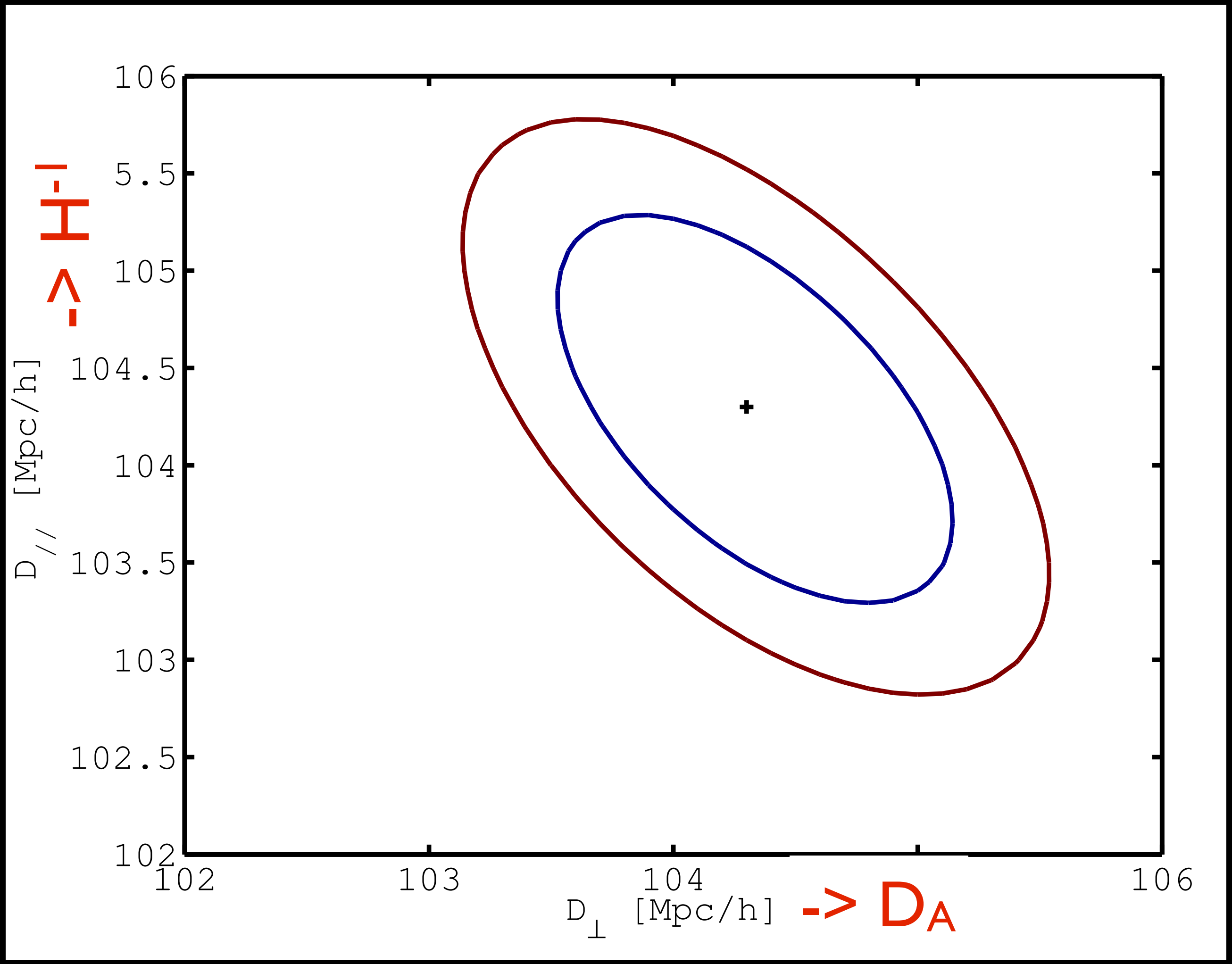
$$H^{-1}_{obs} = H^{-1}_{fid}\frac{D_{||,fid}}{D_{||,obs}},$$

$$D_{A,obs} = D_{A,fid}\frac{D_{\perp,fid}}{D_{\perp,obs}}.$$



Next we create theoretical models that include different systematics and and observational effects.

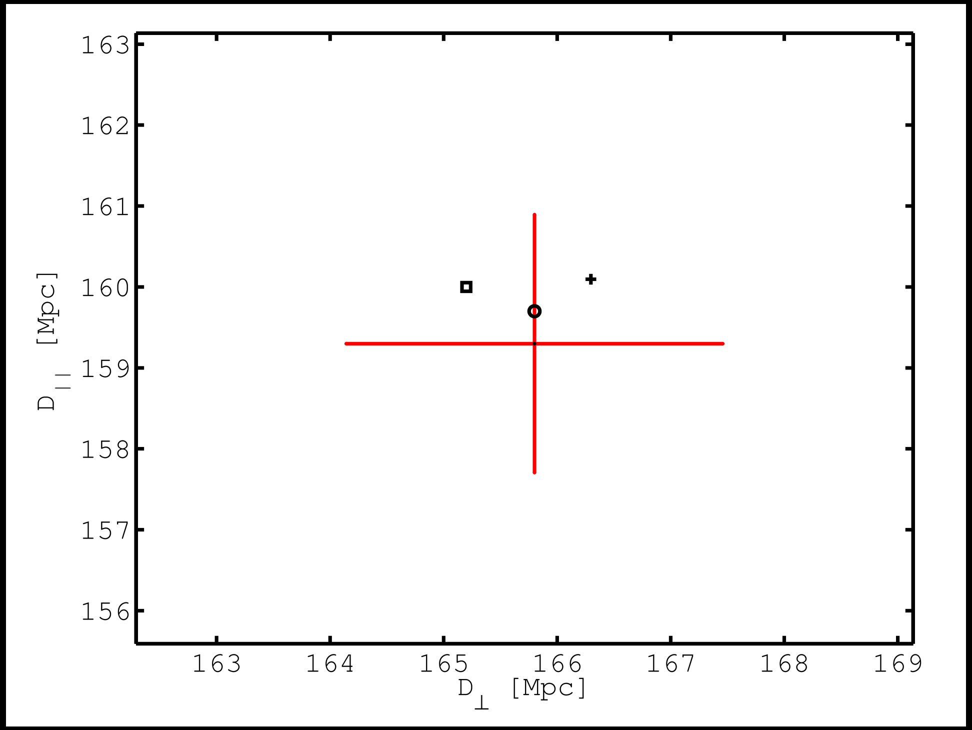
In the fiducial case we obtain a simultaneous measurement of D_A and H^{-1}



Anisotropic BAO Peaks

Will certain systematic uncertainties effect our methodology to reliably estimate the peak location?

we show the effect of changing the bias factor on the derived distance measures. We find that values of b = 1.2, 1.4,1.6, 1.8 all give consistent values of $D_{//}$ and $D_{\perp}$.



We also checked the effect of shifting the overall shape of the spectrum and looked at Linear vs NonLinear templates. However all give 1% level or less deviations on the distances. So our fitting function seems to have enough freedom to accommodate many unknown factors that, in the end, we don't want to deal with!

Anisotropic BAO Peaks

Modelling RSD effect

We show the derived distance measurements using models with various σv choices, of 0, 2, 4, 6, 8 Mpc/h. We find a significant trend with these values of σv with either D// and D⊥

But as we can see both D// and D⊥ can be modelled using a simple function:

$$D(\mu) = D^{fid}(\mu) + \alpha(\mu) + \beta(\mu)\sigma_v^2,$$

Although the dashed lines show 1% and 4% increase in H-1 which follows closely the σv induced anisotropy, so there will be some degeneracy.

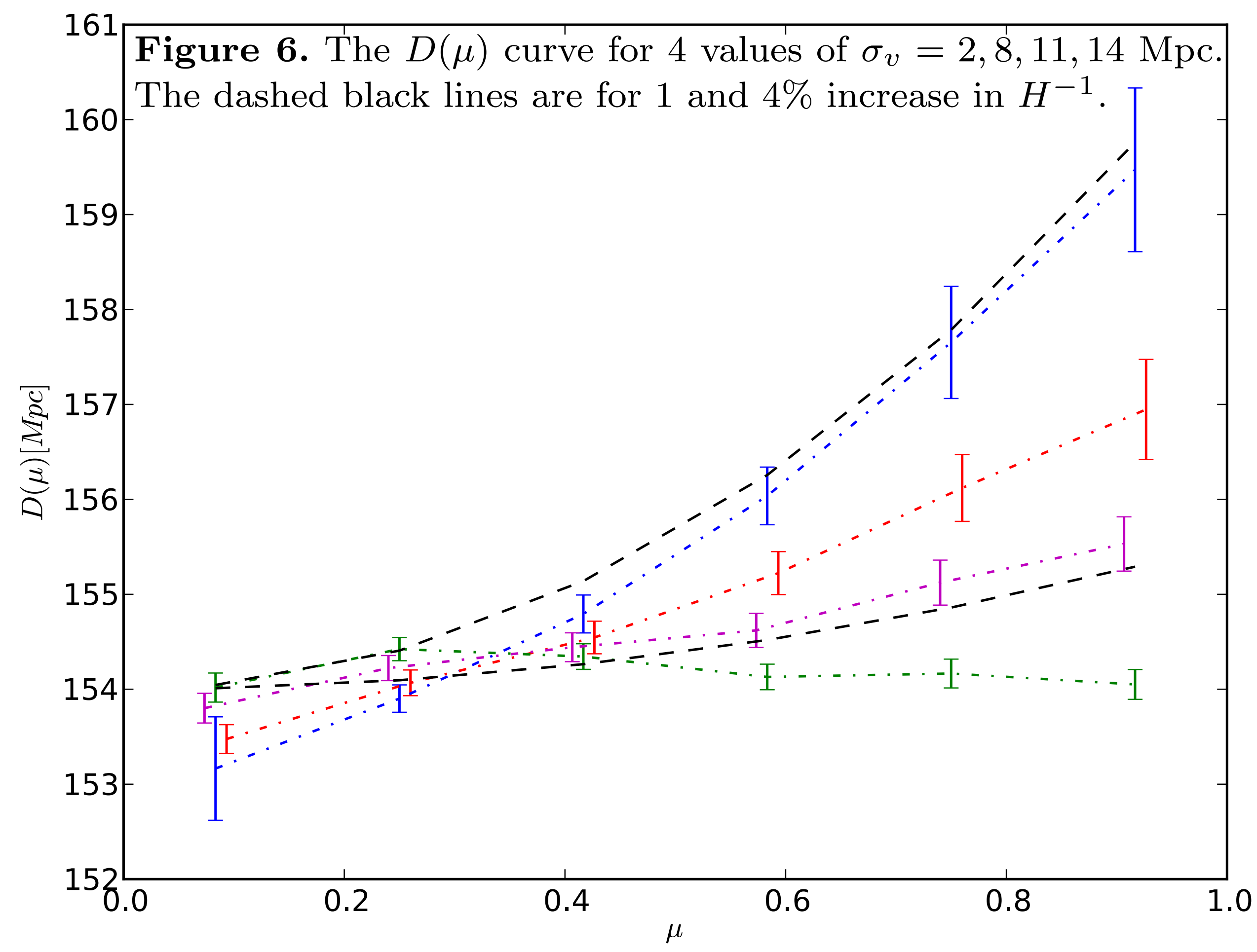


Figure 6. The $D(\mu)$ curve for 4 values of $\sigma_v = 2, 8, 11, 14$ Mpc. The dashed black lines are for 1 and 4% increase in H^{-1}.

	Ω_Λ	0.62		0.68		0.73	
		α_i	β_i	α_i	β_i	α_i	β_i
μ_i	0.08	-0.18	-0.004	-0.15	-0.004	-0.21	-0.004
	0.25	0.21	-0.003	0.07	-0.002	0.10	-0.002
	0.42	-0.17	0.002	-0.10	0.002	-0.09	0.002
	0.58	-0.51	0.009	-0.47	0.010	-0.42	0.009
	0.75	-0.77	0.018	-0.68	0.018	-0.65	0.018
	0.92	-1.07	0.027	-0.88	0.026	-0.89	0.027

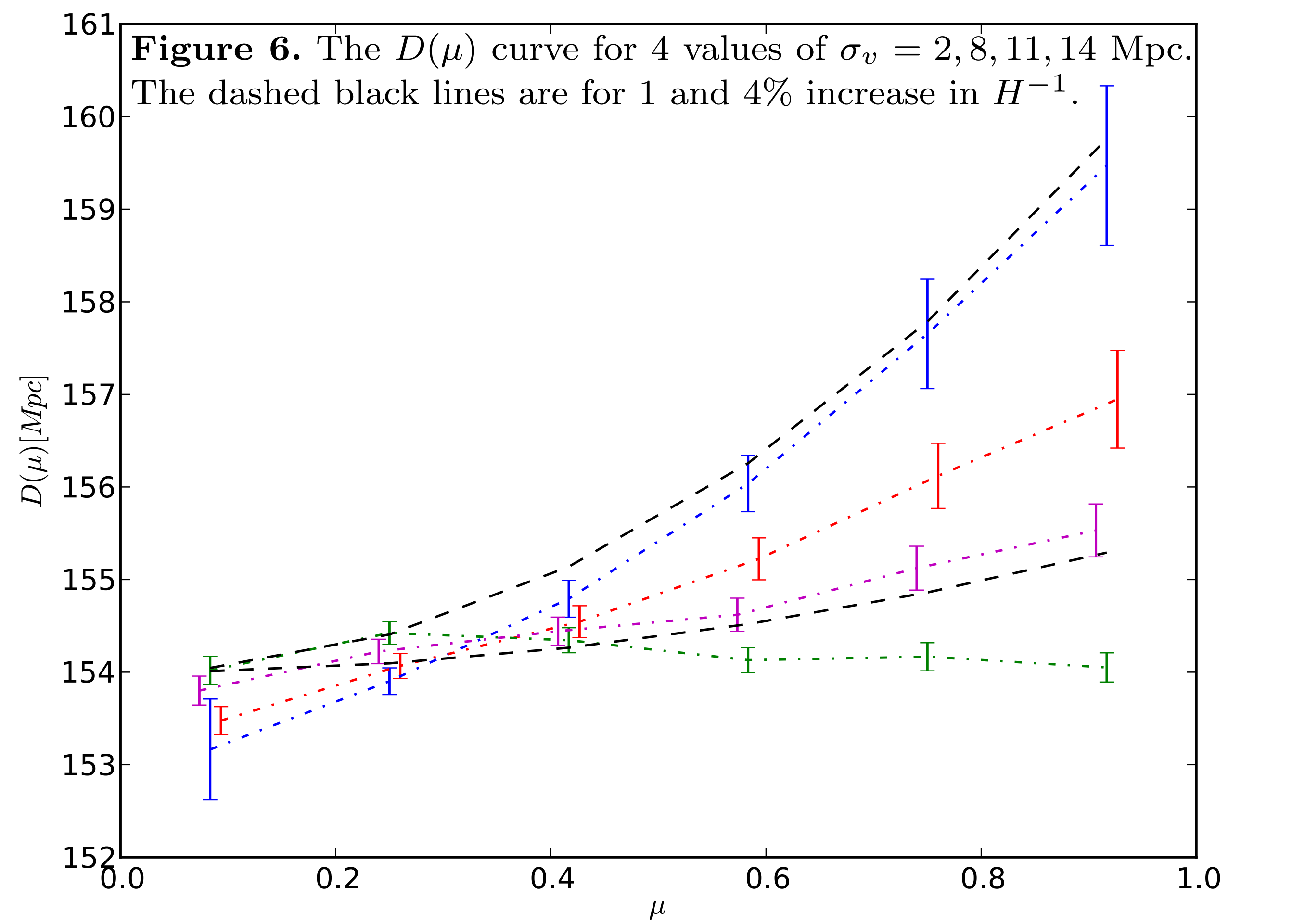
Anisotropic BAO Peaks

Modelling RSD effect

Modeling the RSD effect allows us to make percent level predictions of Da, H for future surveys, like DESI

Firstly we fit the case without RSD. If we do not correct for the RSD effect we know from previous tests that our results on H^{-1} will be necessarily biased. We find $D_{||} = 155.15 \pm 0.51$ Mpc and $D_{\perp} = 154.04 \pm 0.30$ Mpc that results in the following constraints; $D_A = 1399.71^{+2.71}_{-2.74}(0.32^{-0.20}_{+0.19}\%)$ and $H^{-1} = 3196.79^{+10.57}_{-10.44}(-1.17 \pm 0.32\%)$, where the percentage denotes the deviation from fiducial model.

$D_{||} = 154.92^{+0.51}_{-2.29}$ Mpc and $D_{\perp} = 153.90^{+0.25}_{-0.25}$ Mpc with $\sigma_v = 6.8^{+2.0}_{-6.8}$ Mpc, which leads to $D_A = 1401.01^{+2.29}_{-2.26}(0.42^{-0.17}_{+0.16}\%)$ and $H^{-1} = 3201.66^{+47.94}_{-10.39}(-1.02^{+1.48}_{-0.32}\%)$.



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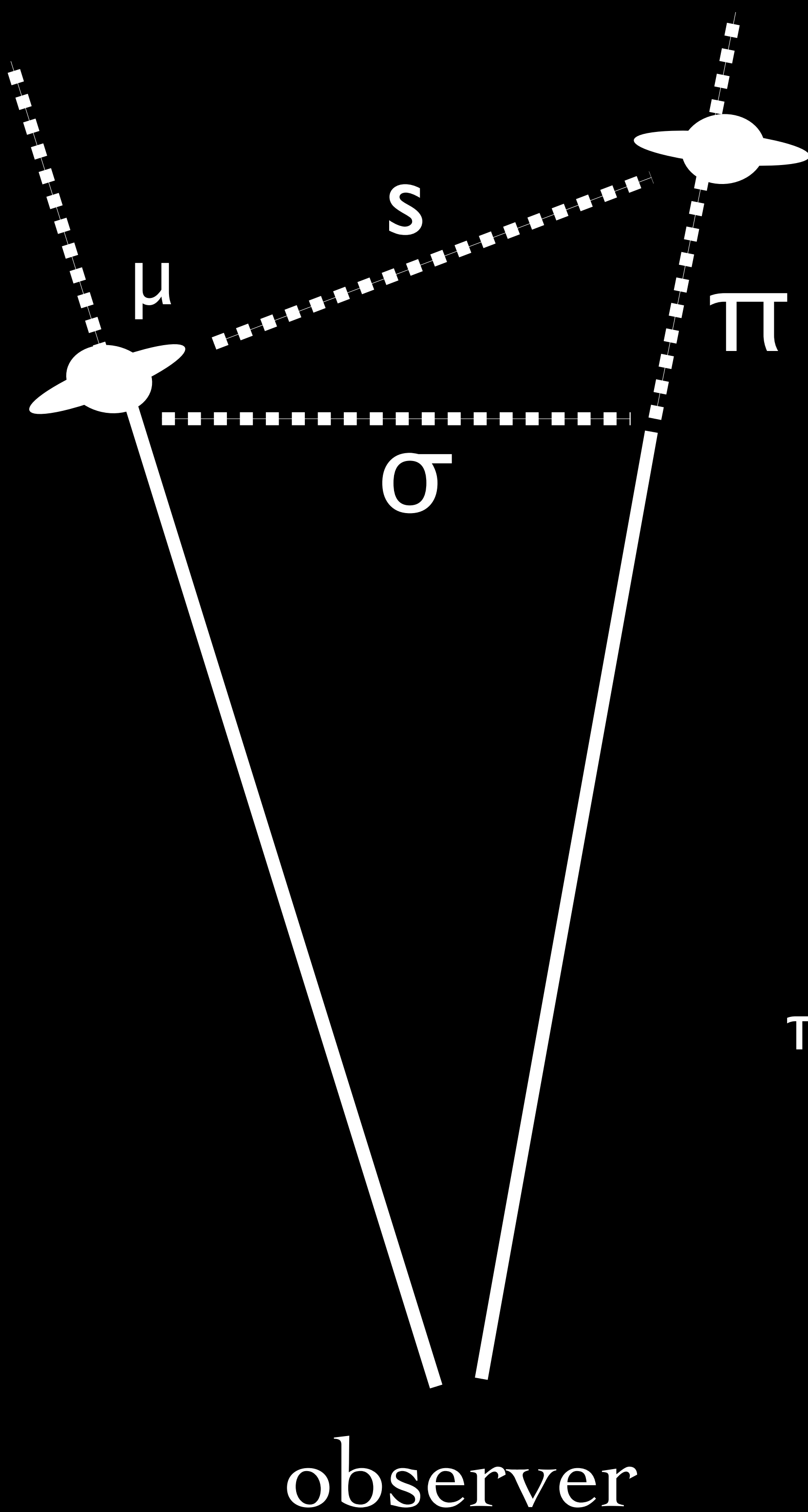
	0.92	-1.07	0.027	-0.88	0.026	-0.89	0.027

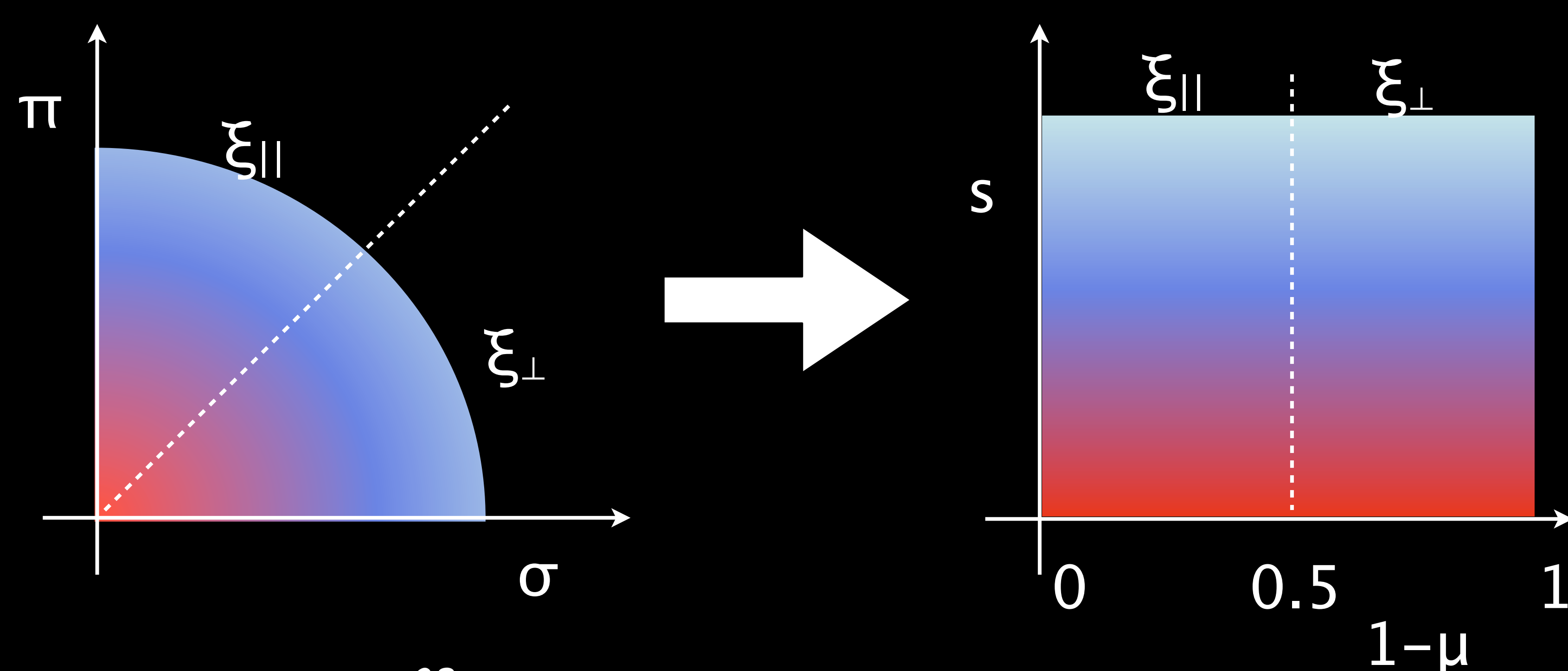
AP effect & Clustering Shells

We don’t need a standard ruler for AP effect....



$$\xi(\sigma,\pi) = \frac{DD(\sigma,\pi) - 2DR(\sigma,\pi) + RR(\sigma,\pi)}{RR(\sigma,\pi)}$$

DD - data-data pairs
DR - data-random pairs
RR - random-random pairs



Clustering Shells

with Xiao-Dong Li & Changbom Park (KIAS) - arXiv:1504.00740

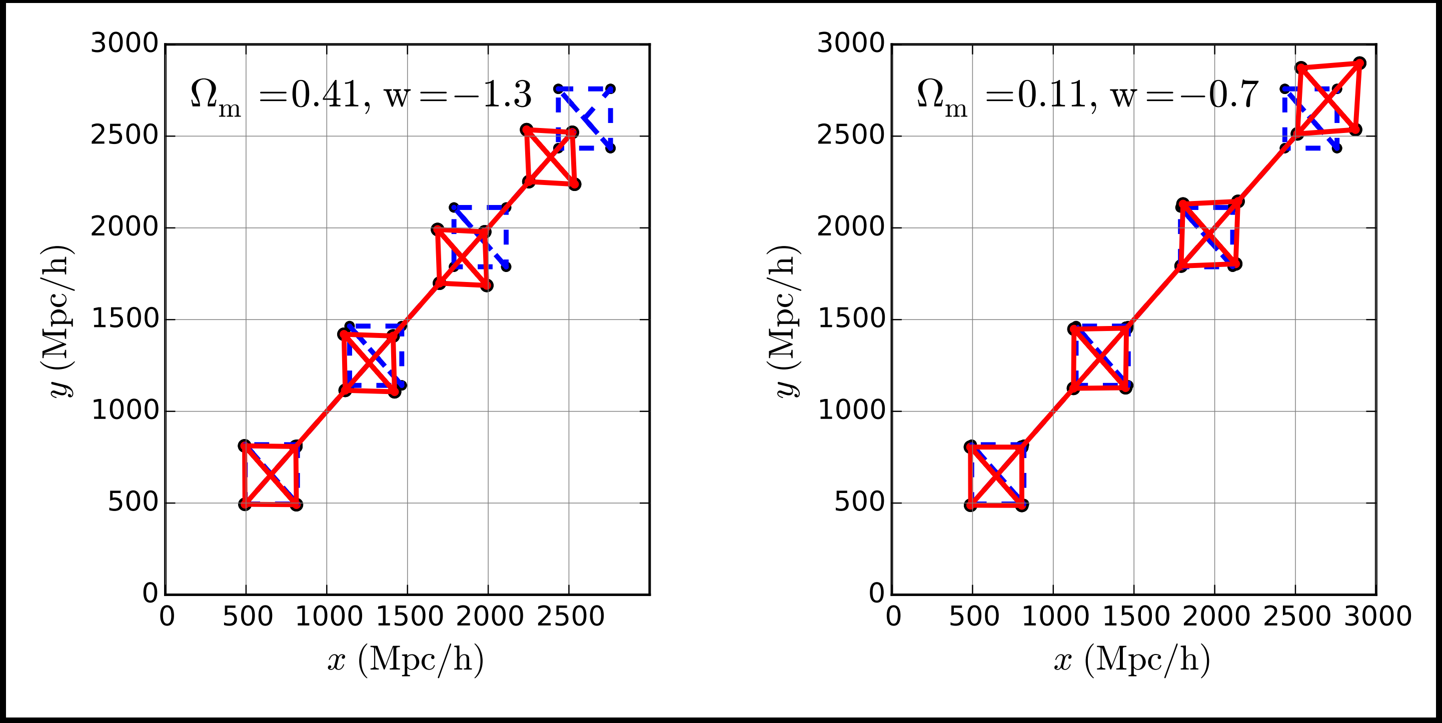
Even without a standard ruler, we can measure the clustering along and perpendicular to the line of sight and thus constrain the combination of D_A and H^{-1}

In this statistical analysis we aim to constrain the AP effect. Rather than using the BAO peak position, we use the integrated clustering signal in different directions.

$$\xi_{\Delta s}(\mu) \equiv \int_{s_{\rm min}}^{s_{\rm max}} \xi(s,\mu)\, ds.$$

Pictorially what happens to cosmological positions if translated using an incorrect cosmological model.

For Om=0.11, w=-0.7, we see a LOS shape compression and volume shrinkage.

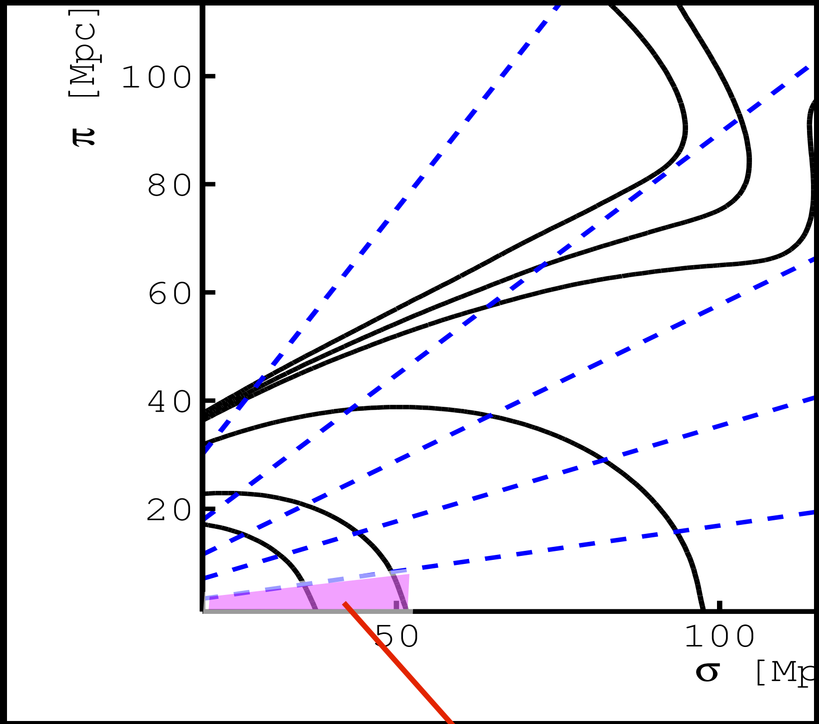


For Om=0.41, w=-1.3, we see a stretch of the shape in the LOS direction and magnification of the volume

Clustering Shells

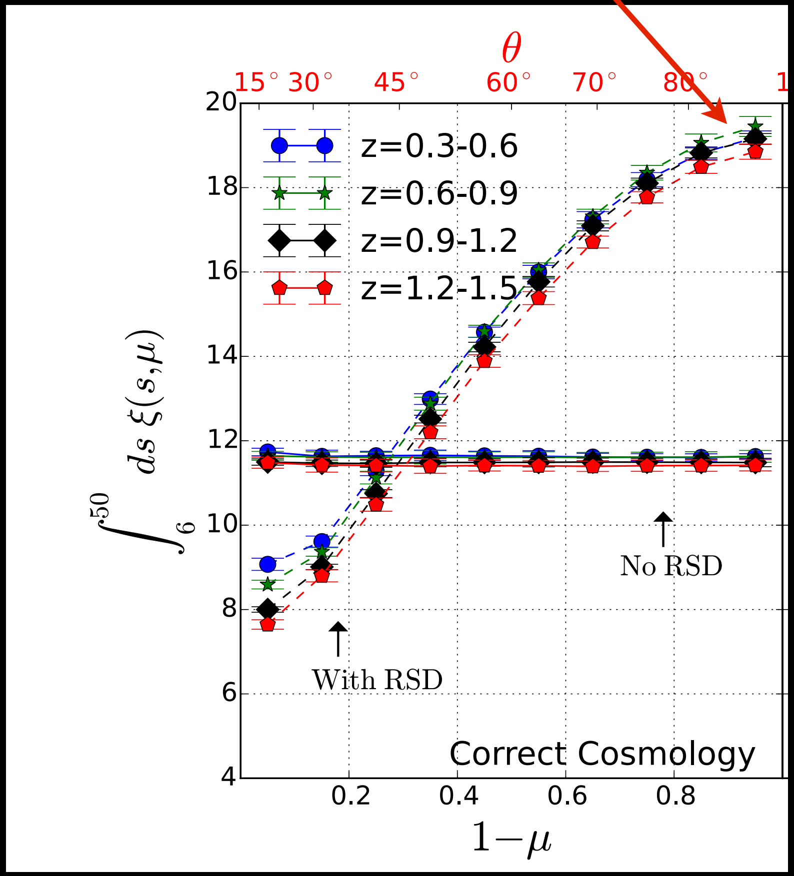
The integrated clustering strength as a function of angle at varies redshifts.

$$\xi_{\Delta s}(\mu) \equiv \int_{s_{\min}}^{s_{\max}} \xi(s,\mu)\ ds.$$



In the no RSD case in the correct cosmology the curves are flat.

With RSDs we see much more variation in shape and amplitude.



Clustering Shells

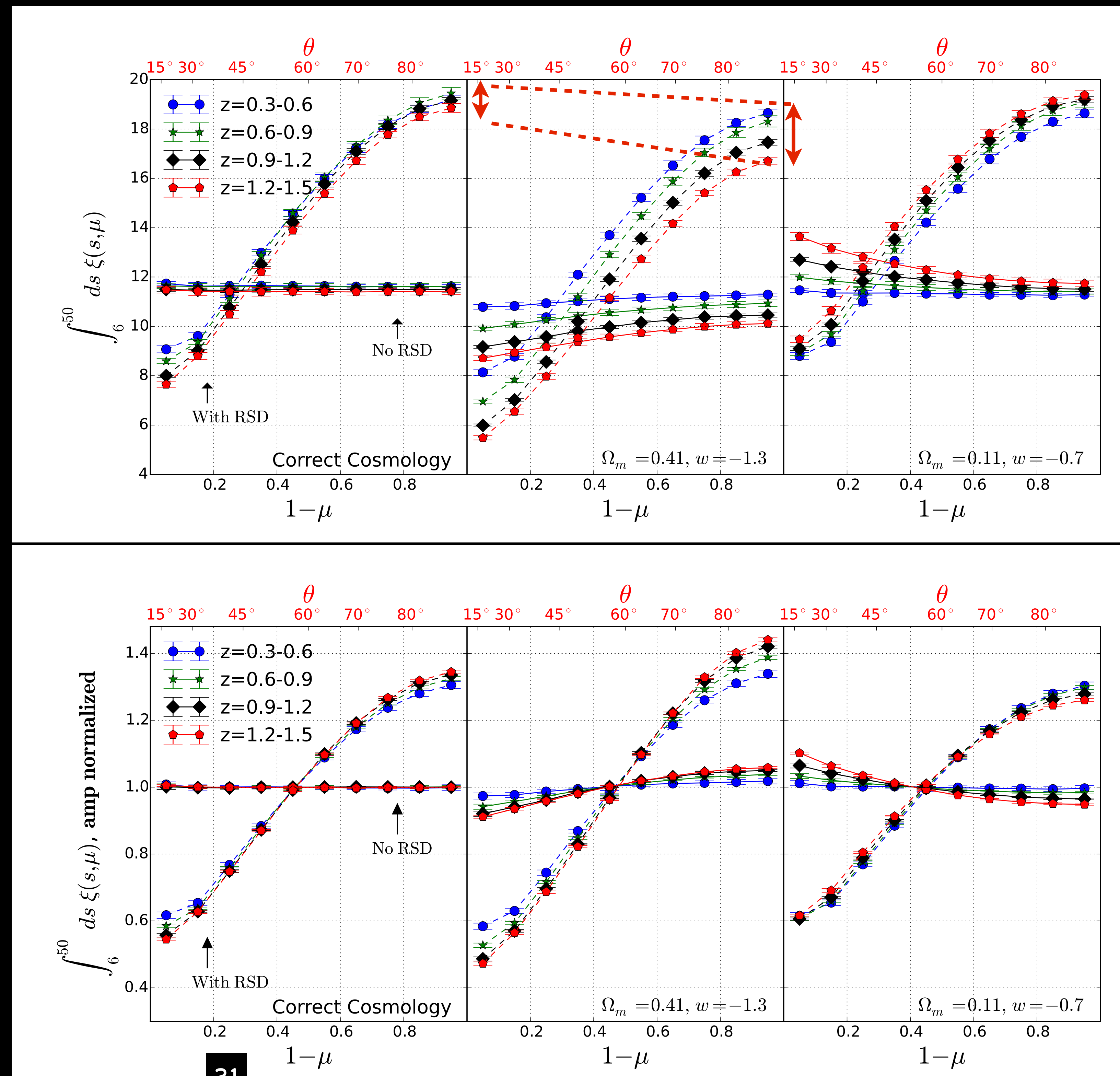
The integrated clustering strength as a function of angle at varies redshifts.

In the no RSD case in the correct cosmology the curves are flat. In the wrong cosmologies they are distorted.

With RSDs we see much more variation in shape and amplitude.

If we normalise the curves, then we remove amplitude information and minimise the volume effect thus focusing on a pure AP measurement.

Using mock many catalogues drawn from the Horizon Run simulations (from Juhan Kim, KIAS)

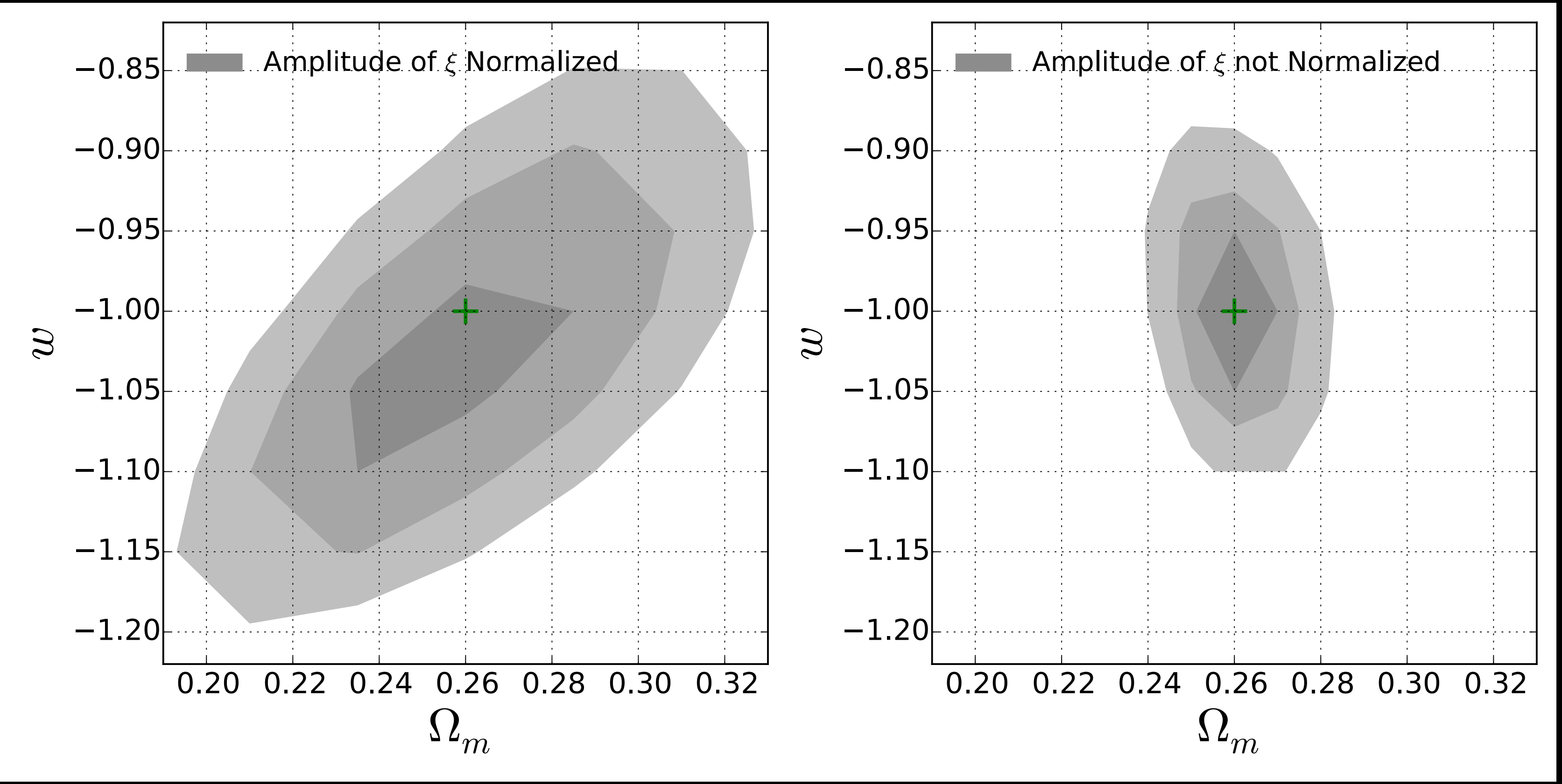


Clustering Shells

We construct a likelihood function by requiring that the shape change as a function of redshift is minimized.

$$H(z) = H_0\sqrt{\Omega_m a^{-3} + (1-\Omega_m)a^{-3(1+w)}},$$
$$D_A(z) = \frac{1}{1+z}r(z) = \frac{1}{1+z}\int_0^z \frac{dz'}{H(z')},$$

$$\frac{[\Delta r_\parallel/\Delta r_\perp]_{\rm wrong}}{[\Delta r_\parallel/\Delta r_\perp]_{\rm true}} = \frac{[D_A(z)H(z)]_{\rm true}}{[D_A(z)H(z)]_{\rm wrong}},$$
$$\frac{\rm Volume_{wrong}}{\rm Volume_{true}} = \frac{[D_A(z)^2/H(z)]_{\rm wrong}}{[D_A(z)^2/H(z)]_{\rm true}},$$



The clustering shells provide a similar constraints to those obtained from standard BAO analysis.

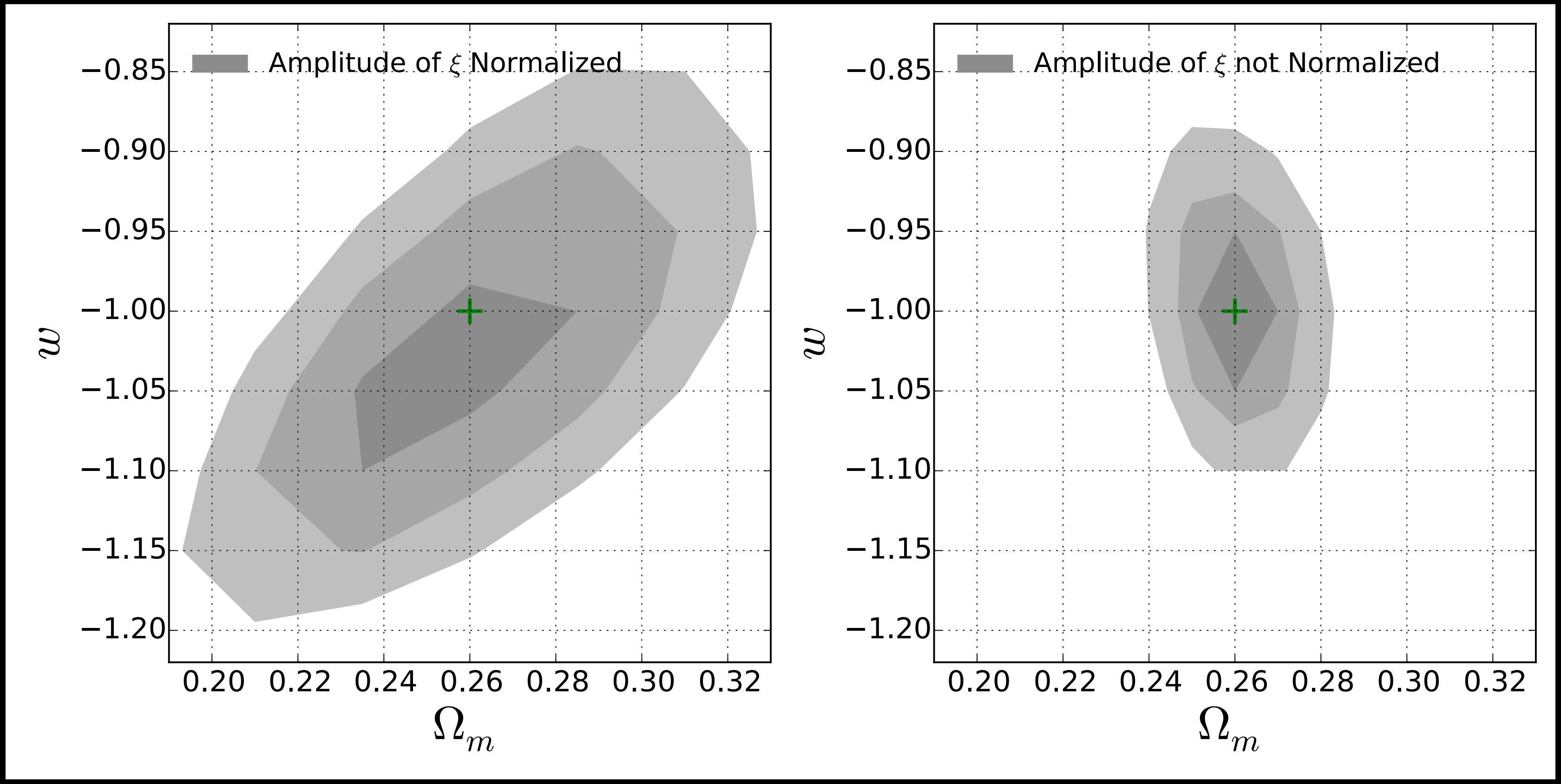
The volume effect, which causes redshift evolution in the amplitude of 2pCF, leads to very tight constraint on cosmological parameters. But it suffers from systematic effects of growth of clustering and the variation of galaxy sample with redshift.

Clustering Shells

We construct a likelihood function by requiring that the shape change as a function of redshift is minimized.

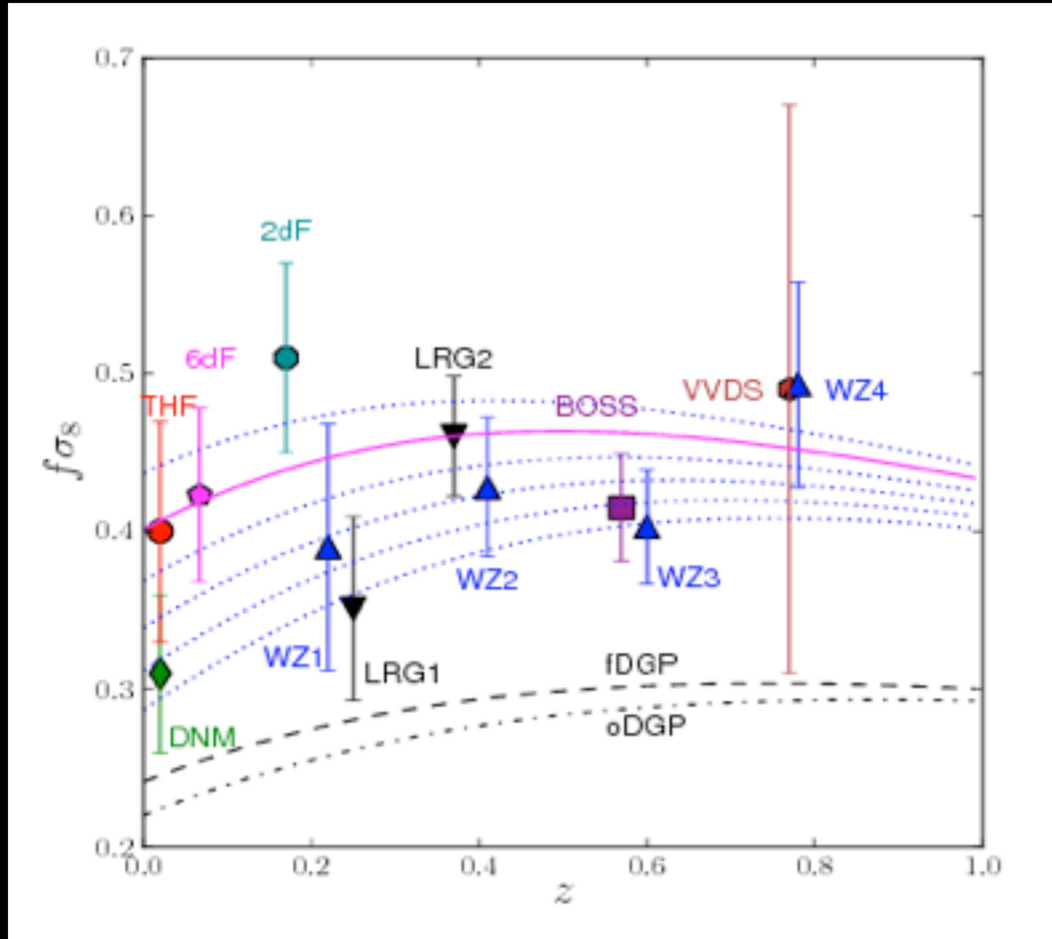
$$H(z) = H_0\sqrt{\Omega_m a^{-3} + (1-\Omega_m)a^{-3(1+w)}},$$
$$D_A(z) = \frac{1}{1+z}r(z) = \frac{1}{1+z}\int_0^z \frac{dz'}{H(z')},$$

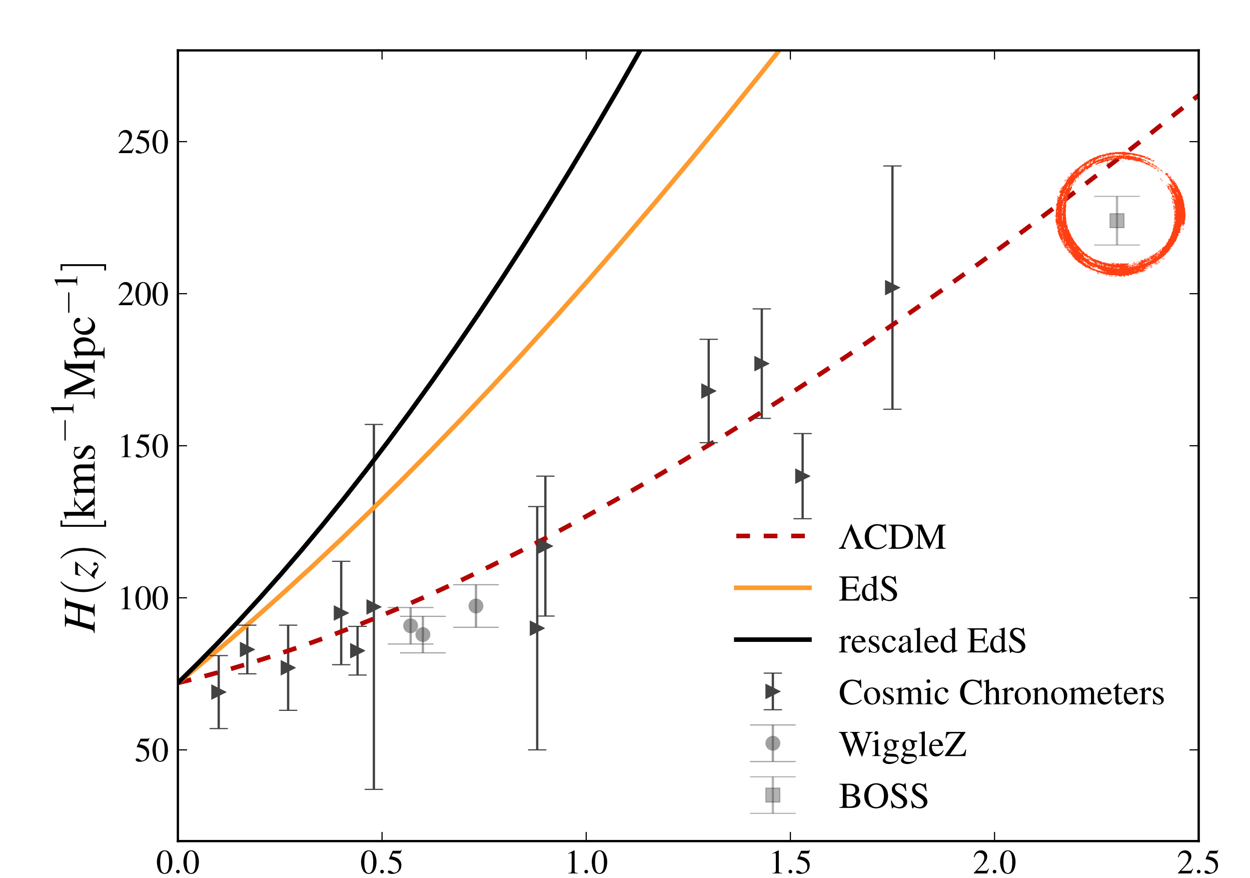
$$\frac{[\Delta r_{\parallel}/\Delta r_{\perp}]_{\rm wrong}}{[\Delta r_{\parallel}/\Delta r_{\perp}]_{\rm true}} = \frac{[D_A(z)H(z)]_{\rm true}}{[D_A(z)H(z)]_{\rm wrong}},$$
$$\frac{\rm Volume_{wrong}}{\rm Volume_{true}} = \frac{[D_A(z)^2/H(z)]_{\rm wrong}}{[D_A(z)^2/H(z)]_{\rm true}},$$



Proof of concept

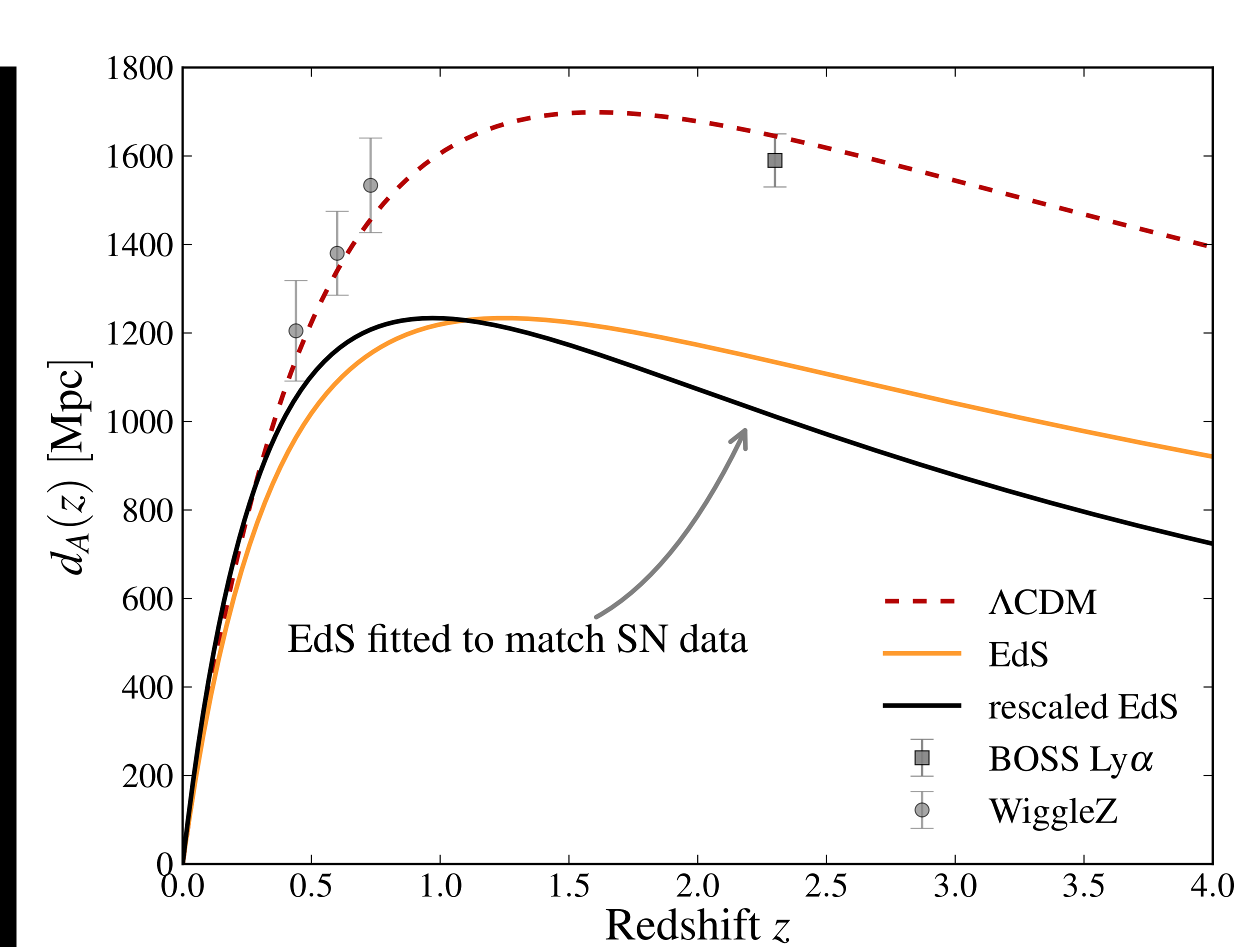
Currently we are applying this to most recent BOSS data.





What we want....

Model independent measurements of Growth Rates and fundamental metric quantities like a, a^dot, H(z), Da - at various redshifts or cosmic times



We are are pushing to higher redshift and reducing errorbars and trying to remove model dependences from our analysis, but it's not easy.

Conclusions - I

We wanted clean measurements of Da and H(z) as they are fundamental quantities that describe the geometry and evolution of the background universe.

- we have shown that the clustering 'peak' give us an unbiased constraint on these quantities

- the 'clustering shells' are also promising....

And this technique will soon be applied to BOSS data

Probing Scalar Field Theories

Light scalar fields coupled to matter (baryons) are predicted by many theories of HEP beyond the standard model.

•

Coupled means we have a fifth−force in nature. If it exists, is there any room for cosmological signatures (of the fifth−force)?

•

A fifth−force is strongly constrained from local gravity experiments (inverse square law, solar--system tests, EP).

•

Naive conclusion: Either very short range or very weakly coupled, in other words: no cosmological effects of the fifth−force!

•

Not the case if the field has a screening mechanism. The fifth−force can remain 'hidden' to local experiments!

•

We consider two models that have this property: Chameleon & Symmetron

Probing Scalar Field Theories in redshift-space

We focus our analysis in two specific scalar tensor models: the symmetron model and a particular case of f(R) theories.

Both models include screening mechanisms, which reduce them to general relativity in high density regions and thus pass solar system tests.

N-body simulations from Llinares, Mota etal (2013) arXiv:1307.6748

with David Mota
& Claudio Llinares (U. of Oslo)

Npart=512^3
Side=256Mpc/h
at z=0.0
Dark matter and FoF halos

Model	λ_0	z_{SSB}	β
Symm A	1	1	1
Symm B	1	2	1
Symm C	1	1	2
Symm D	1	3	1

Model	n	$\lvert f_{R0} \rvert$	λ_0
fofr4	1	10^{-4}	23.7
fofr5	1	10^{-5}	7.5
fofr6	1	10^{-6}	2.4

Symmetron Model
Hinterbichler & Khoury (2010)

f(R) Gravity Model
Hu & Sawicki (2007)

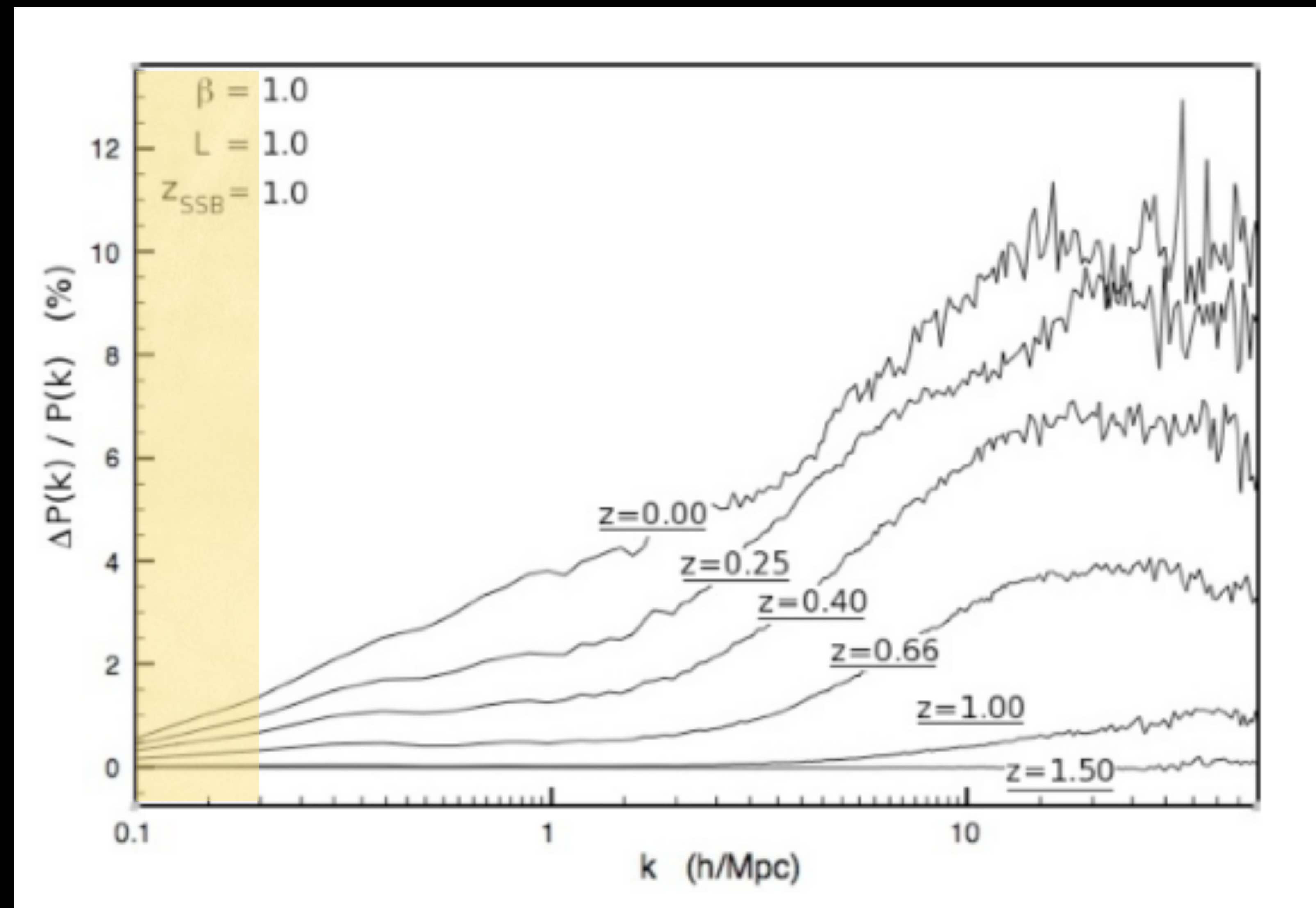
Probing Scalar Field Theories in redshift-space

Percent level difference at relevant scales and redshifts

Isotropic Power Spectrum not very sensitive to information in the velocity field

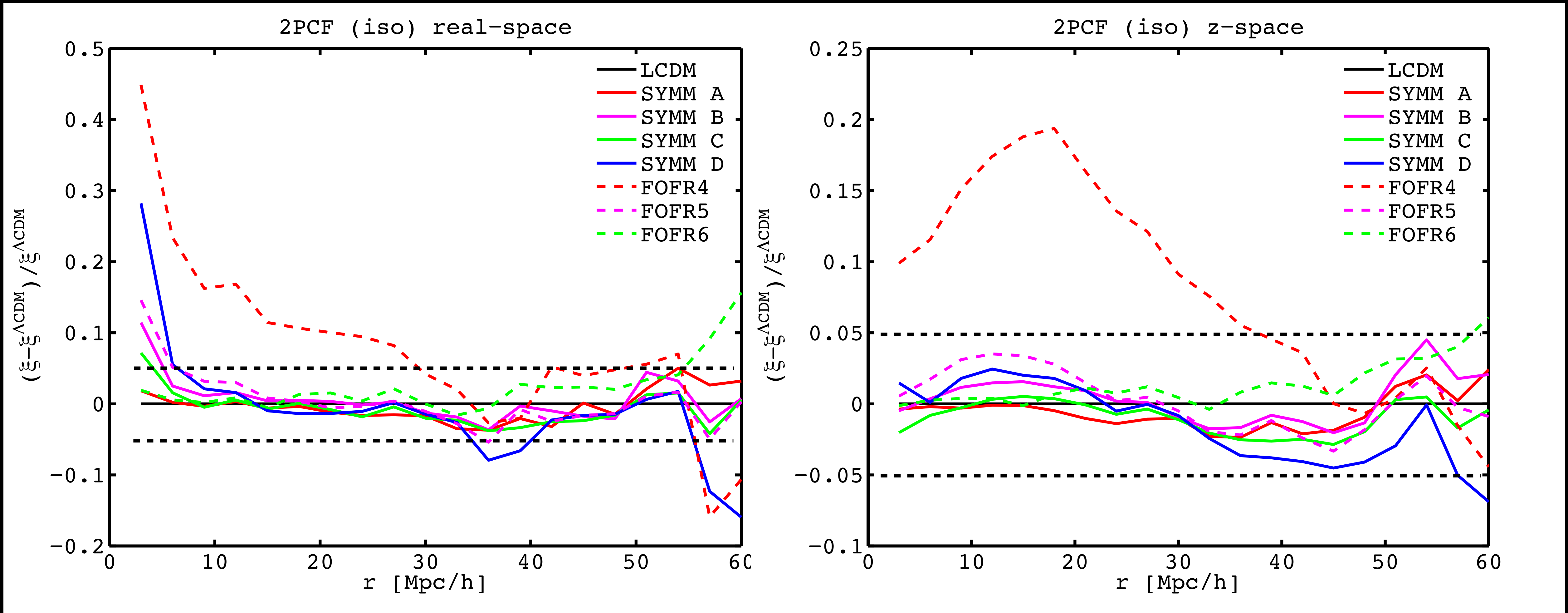
Look in redshift-space using anisotropic statistics?

Symmetron Power Spectrum



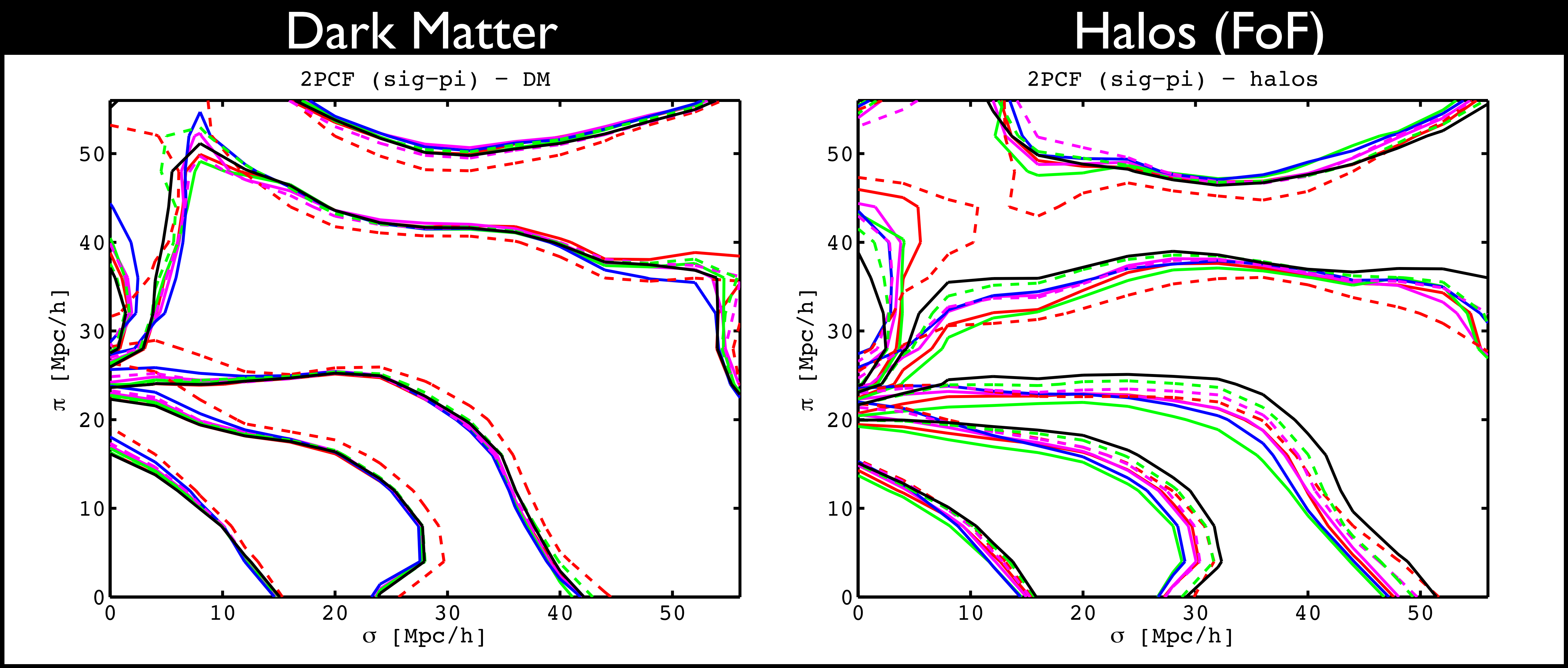
Davis etal 2011

Probing Scalar Field Theories in redshift-space



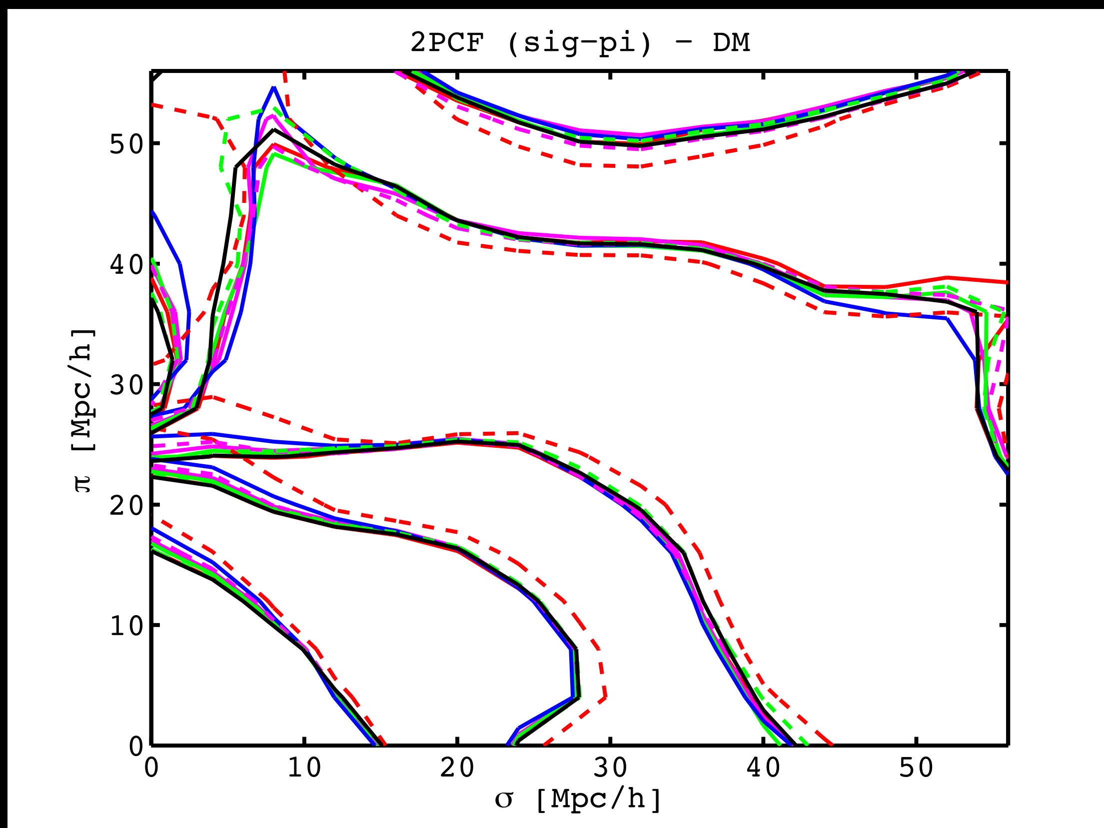
- Using iso-2PCF, more deviation from LCDM in redshift-space
- FOFR4 and SymmD models show largest difference > ~5%
- Maybe we can investigate velocity effect more specifically....

Probing Scalar Field Theories in redshift-space

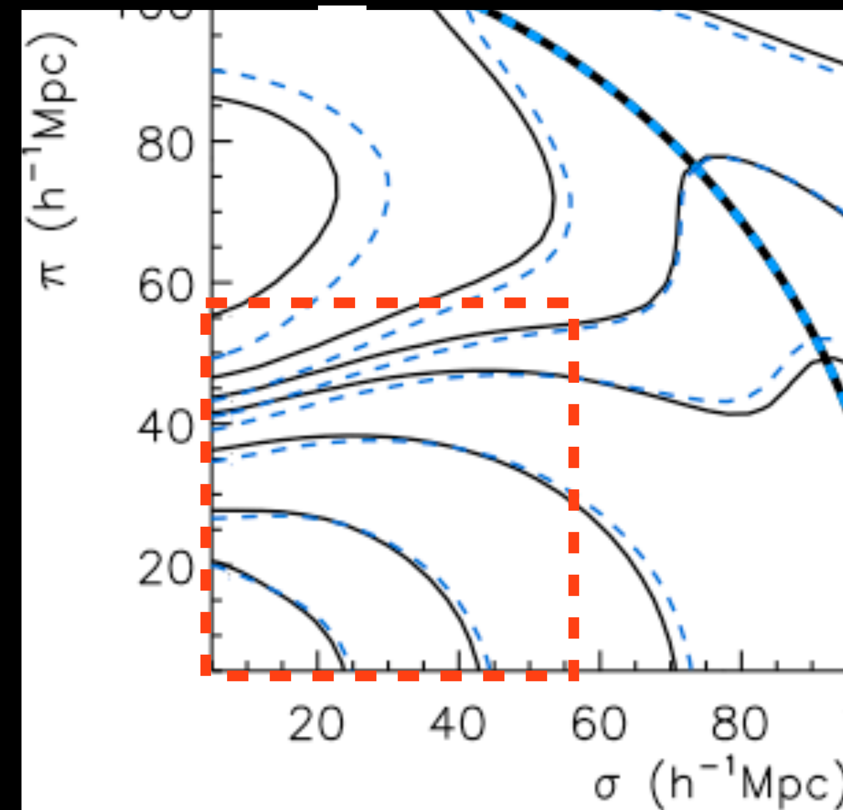


- In anisotropic proj again FOFR4 shows large variation in DM
- Halo clustering exhibits wider dispersion amongst models
- So what? Can we construct a smoking gun test? maybe...

Probing Scalar Field Theories in redshift-space



10% G_theta variation



Remember that the observables of anisotropic clustering have different influences on the shape of the contours.

FOFR4 has an effect similar to G_theta

Since G_theta can be predicted from PLANCK + LCDM, we can hope to disentangle cosmo effects and look for deviations...

3-Point correlations (Bispectrum)

- Complete statistical description requires higher-order correlations
- Expensive (computational time) [redacted]

$$\zeta(r_1, r_2, r_3) = \langle \delta_{gal}(r_1)\delta_{gal}(r_2)\delta_{gal}(r_3) \rangle$$

- Probability of finding pairs/triplets of objects

$$dP = n^3(1 + \xi(r_1) + \xi(r_2) + \xi(r_3) + \zeta(r_1, r_2, r_3))dV_1 dV_2 dV_3$$

'random'

correlated pairs

correlated triangles
early times: $\zeta \sim \xi^2$

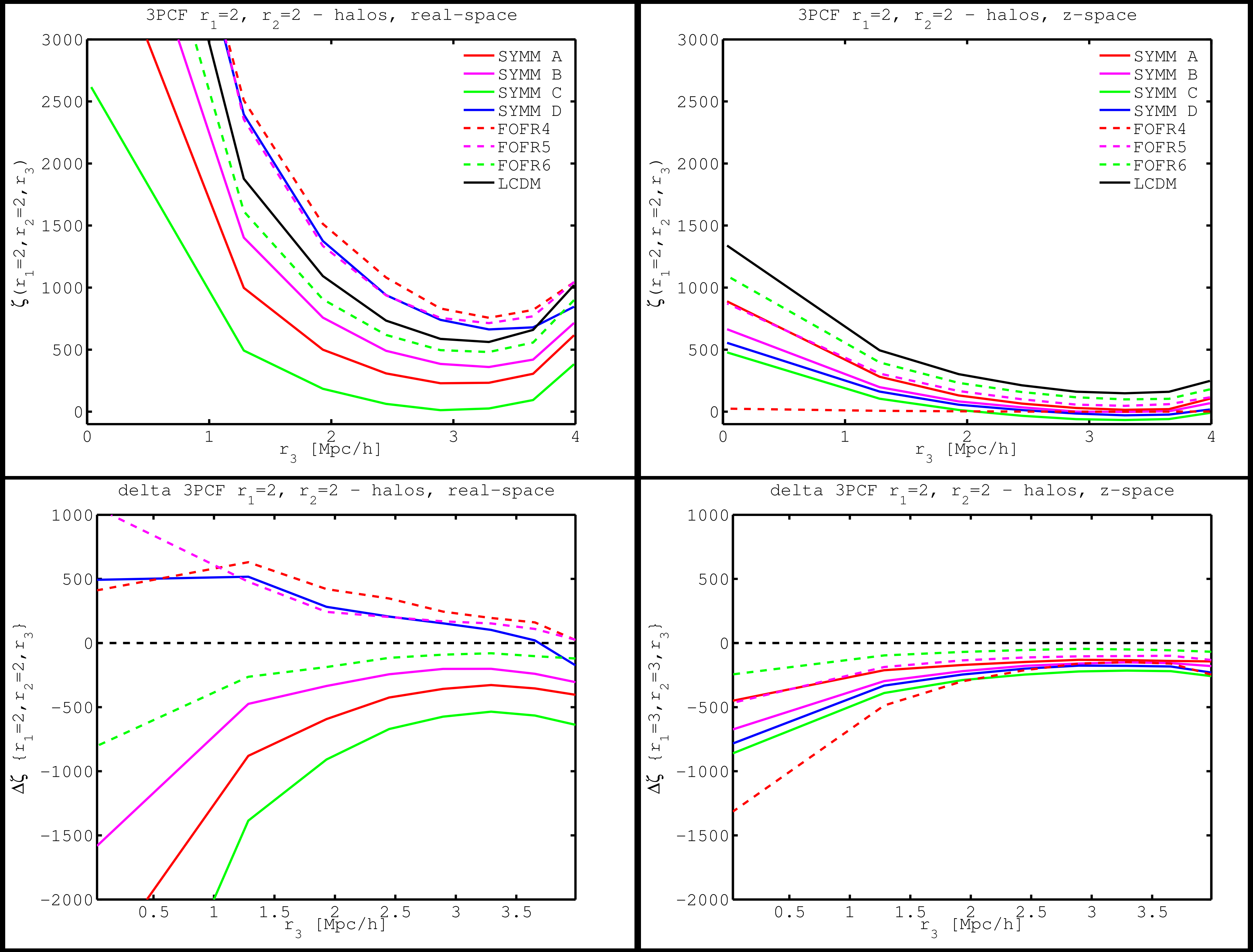
Probing Scalar Field Theories in redshift-space

The 3pcf in various modified gravity simulations

Small scale clustering with s=2, q=1

there is significant dispersion between models which suggest that the 3PCF is a more powerful probe of modified gravitational clustering.

The redshift space clustering tends to flatten the 3PCF, with FOFR4 displaying an extreme case of this.

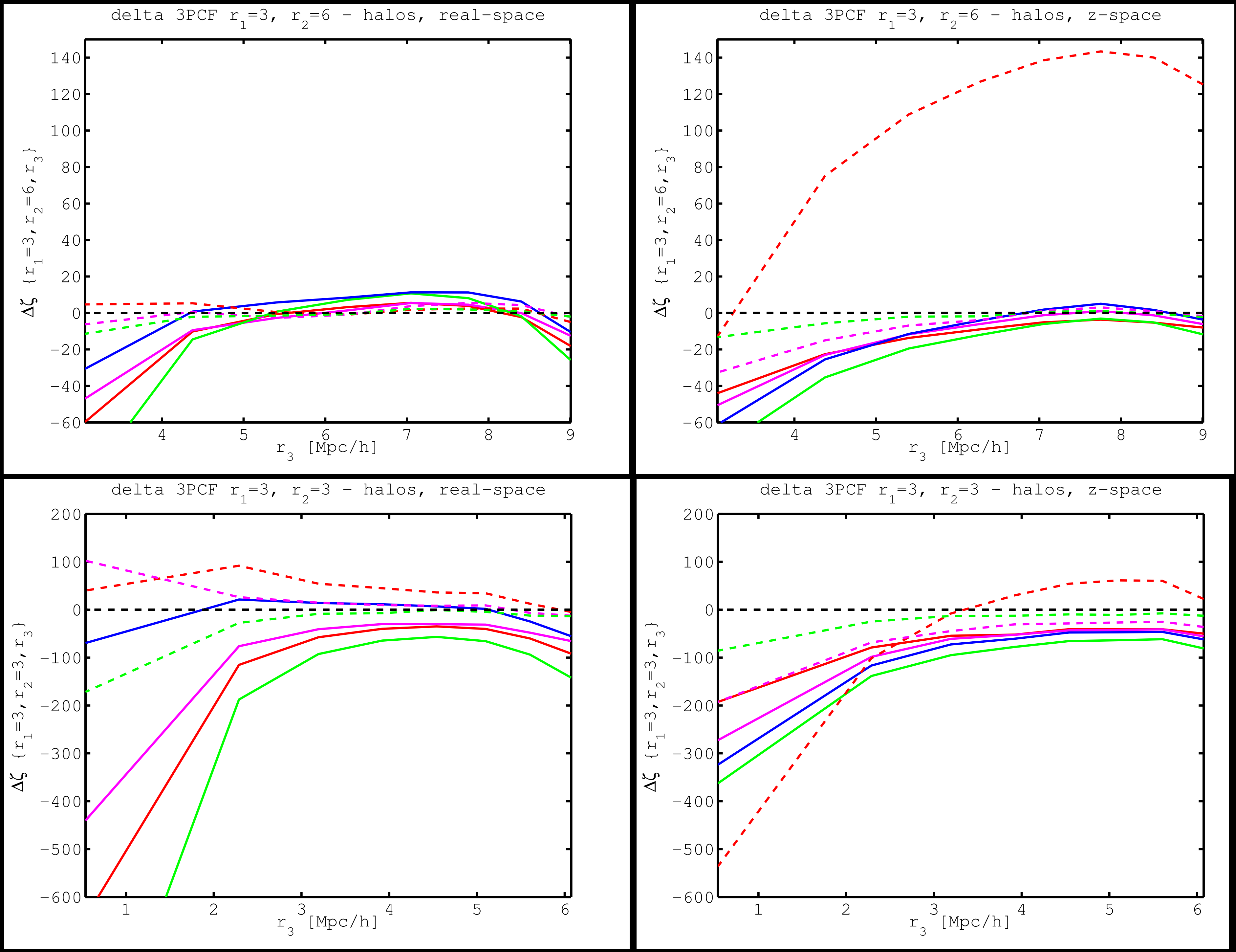


Probing Scalar Field Theories in redshift-space

The 3pcf in various modified gravity simulations

Larger 3pt configuration with: s=3 q=2

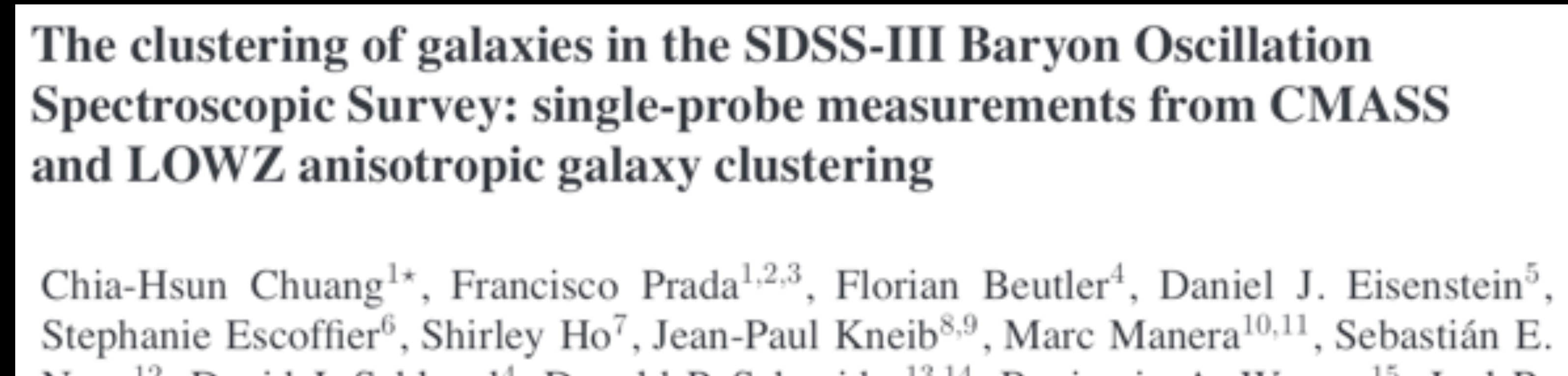
Need an approximate error treatment to determine if deviations between models are larger than statistical fluctuations



Conclusions - II

We hunted for mod. grav. induced variations in the velocity field and the local environment density...

- Measured the redshift-space clustering statistics
- Find deviations from LCDM above exp. error
- redshift 2pcf shows deviations similar to Growth
- Although this is only a qualitative study so far, it is the 1st regarding redshift-space bispectra/3PCF in modified gravity.

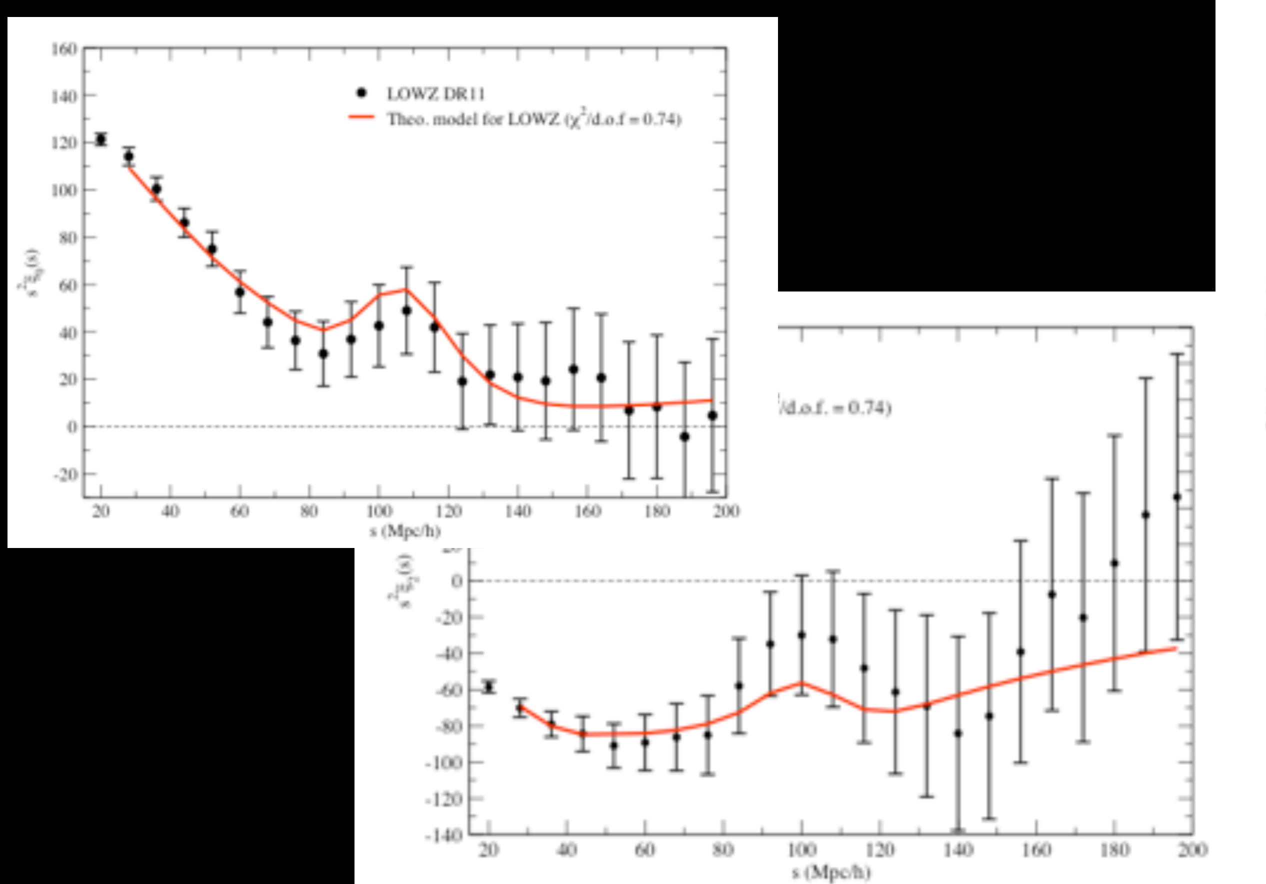

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: single-probe measurements from CMASS and LOWZ anisotropic galaxy clustering

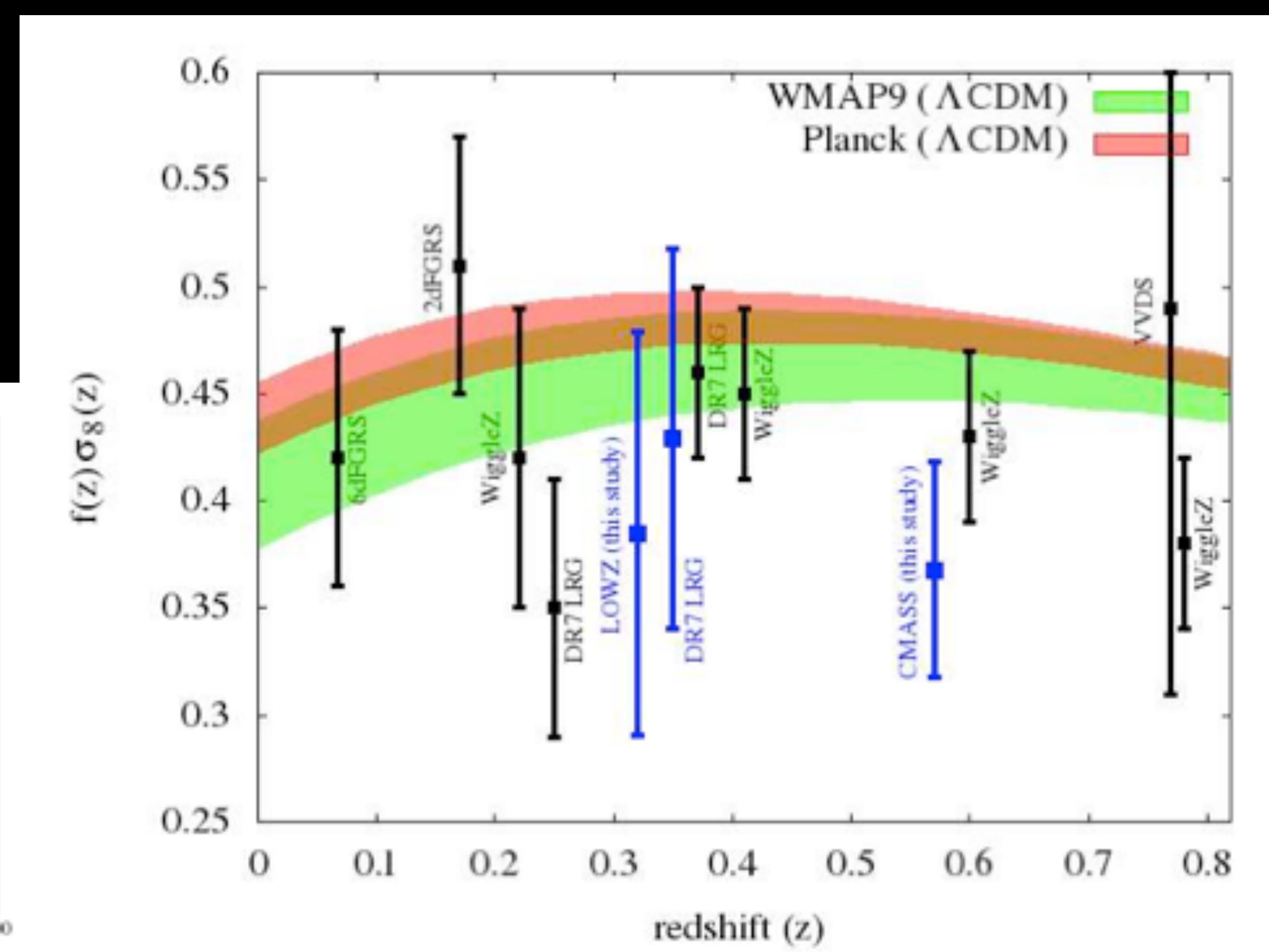
Chia-Hsun Chuang[1*], Francisco Prada[1,2,3], Florian Beutler[4], Daniel J. Eisenstein[5], Stephanie Escoffier[6], Shirley Ho[7], Jean-Paul Kneib[8,9], Marc Manera[10,11], Sebastián E.

arXiv: 1312.4889

they extract cosmological constraints from the measurements of redshift and geometric distortions at quasi-linear scales, modeled using perturbation theory.

They analyze the broad-range shape of the monopole and quadrupole correlation functions of the BOSS DR11 CMASS galaxy sample, at redshift z~0.57

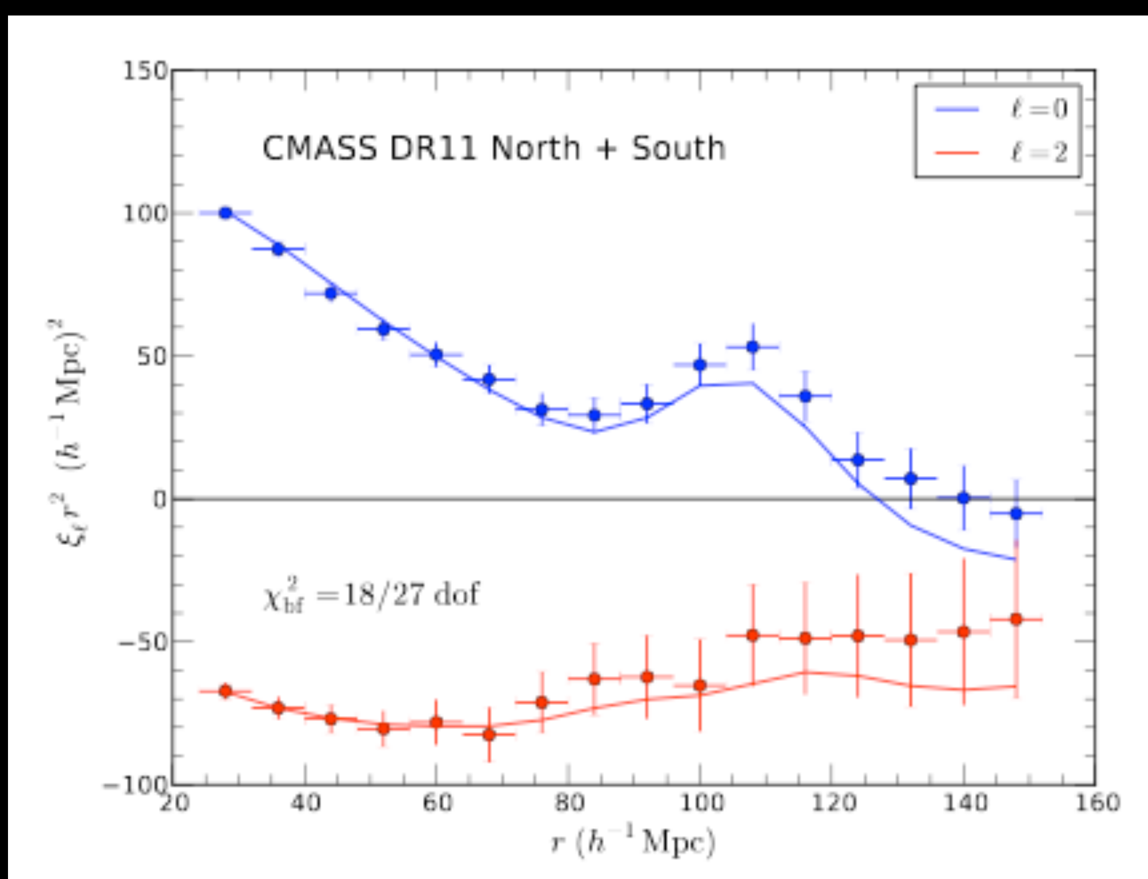


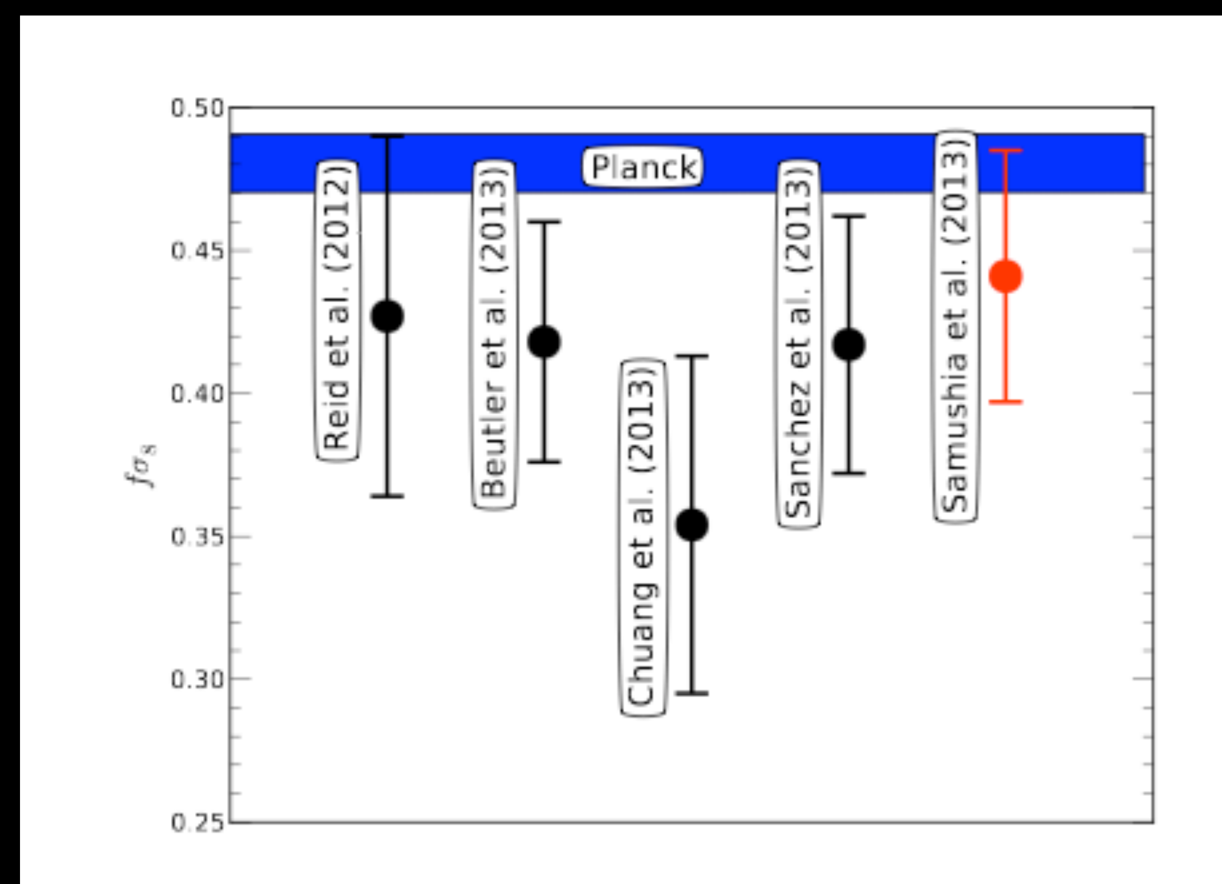


The Clustering of Galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS): measuring growth rate and geometry with anisotropic clustering

Lado Samushia[1,2]⋆, Beth A. Reid[3,4,5], Martin White[3,5], Will J. Percival[1], Antonio J. Cuesta[6,7], Gong-Bo Zhao[1,8], Ashley J. Ross[1], Marc Manera[9,1], Éric Aubourg[10], Flo-

"While our measurements are generally consistent with the predictions of CDM and General Relativity, they mildly favor models in which the strength of gravitational interactions is weaker than what is predicted by General Relativity."





Seeing the light: The luminosity correlation func.

with: Avi Loeb and Maayane Soumagnac

submitting to PRL

The usual galaxy density:

$$\delta_n = b_n \delta_{tot}$$

The mean luminosity of galaxies may depend on environment, through merger rates that are corrected with the local matter density. This can lead to fluctuations in rho_L:

$$\delta_L = (b_n + b_{L;t})\delta_{tot}$$

$b_{L;t}$ - effective bias factor that measures the overall dependence of galaxy luminosity on the underlying difference between the baryon and total density fluctuations.

If we assume that star formation rate per baryon ~ const. then:

$$\langle L \rangle \propto f_b$$

The gas fraction in halos

The Idea

Scale-Dependent Bias of Galaxies from Baryonic Acoustic Oscillations

arxiv: 1009.1393

Rennan Barkana[1] and Abraham Loeb[2⋆]
[1] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel*
[2] *Astronomy Department, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA*

The galaxy correlation function:

$$\xi_n = b_1^2 \xi_{tot} + 2 b_1 b_2 \xi_{add} + b_2^2 \xi_{CIP}$$

and the luminosity correlation function:

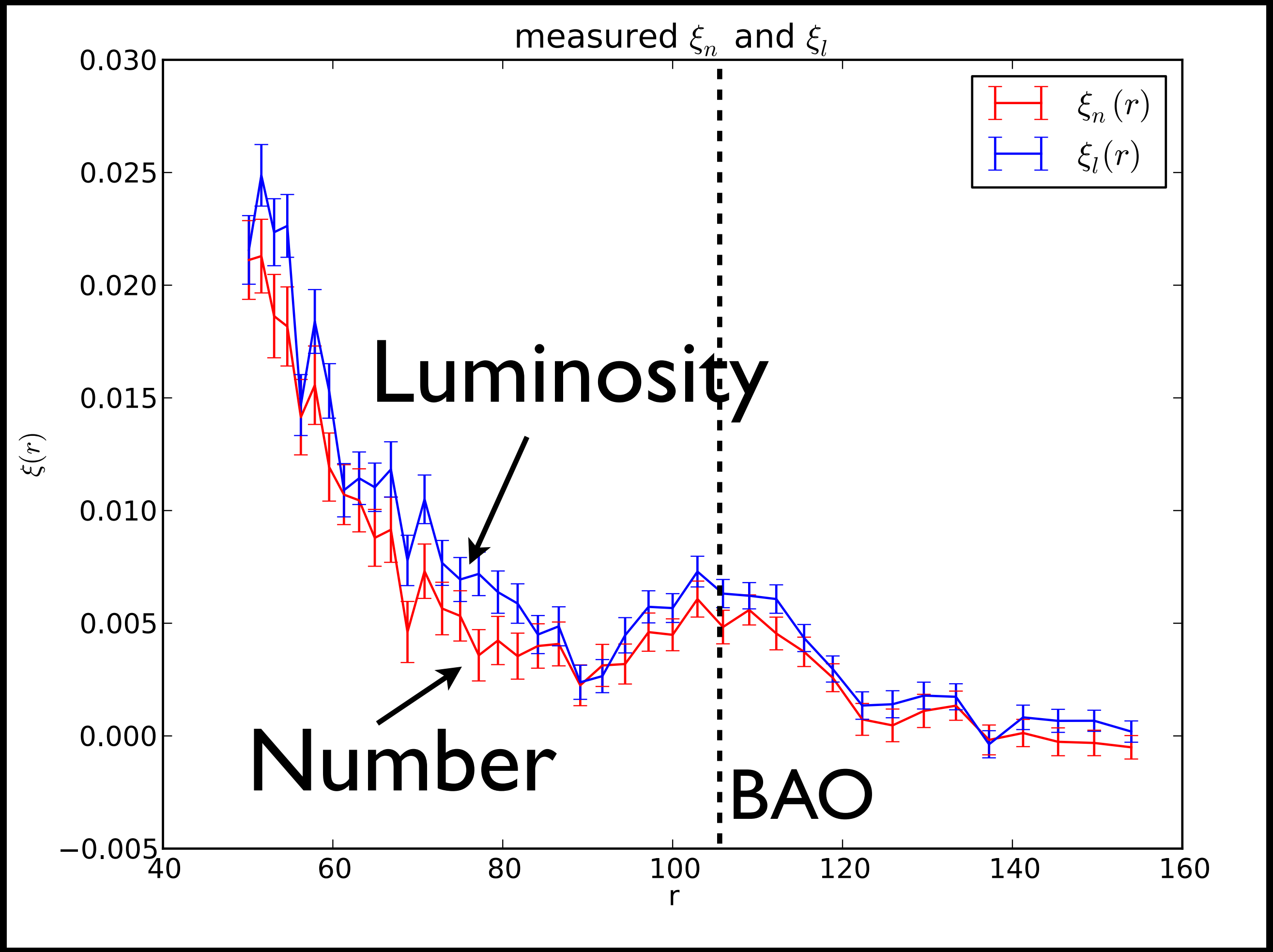
$$\xi_L = (b_1 + b_3)^2 \xi_{tot} + 2(b_1 + b_3(b2 + b_4)\xi_{add} + \ldots$$
$$\ldots + b_{CIP} \xi_{CIP}$$

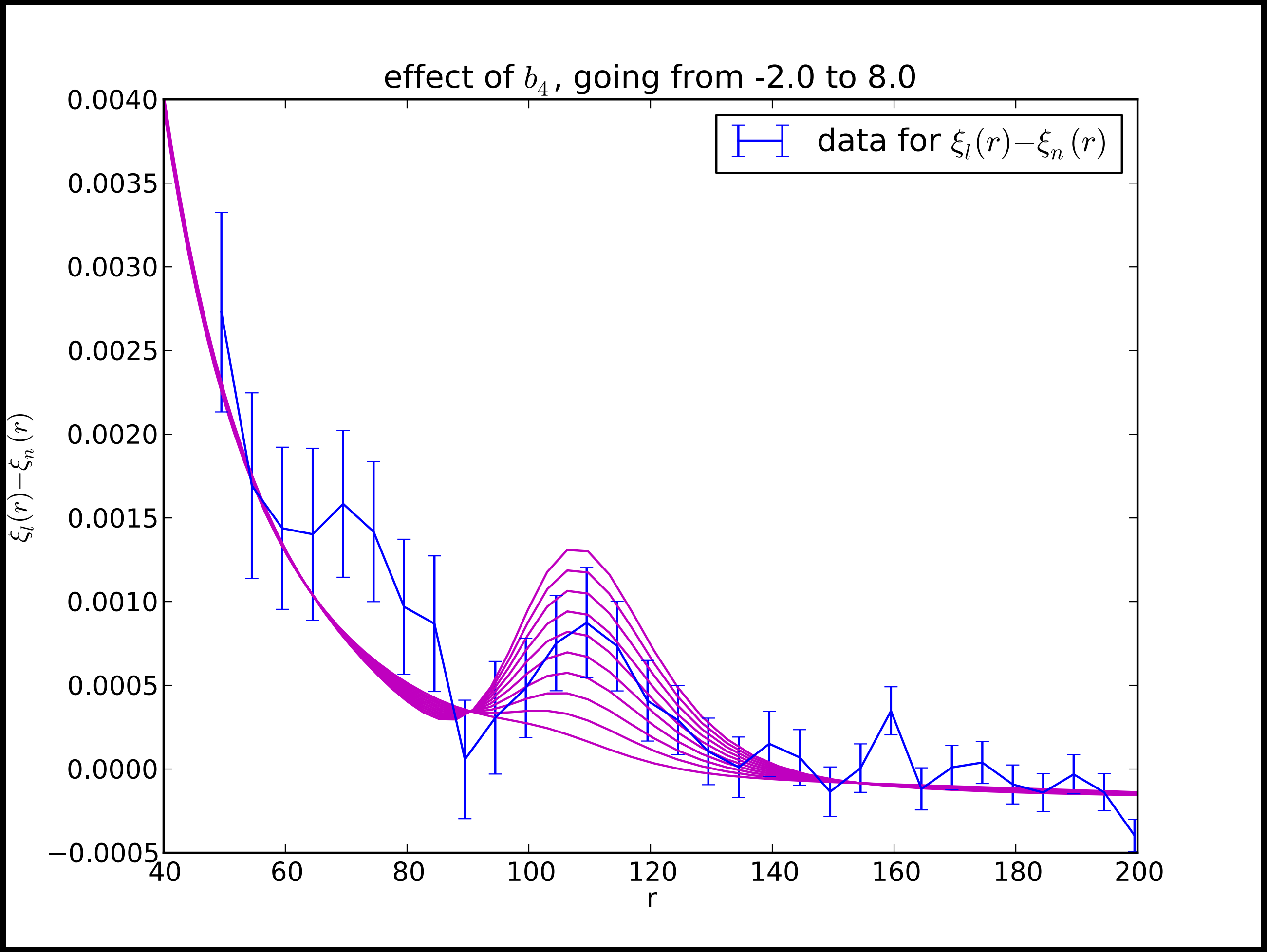
and the additional factor:

$$\xi_{add} = \int k^2 (r(k) - r_{LSS}) P(k) j_0(ks) dk$$

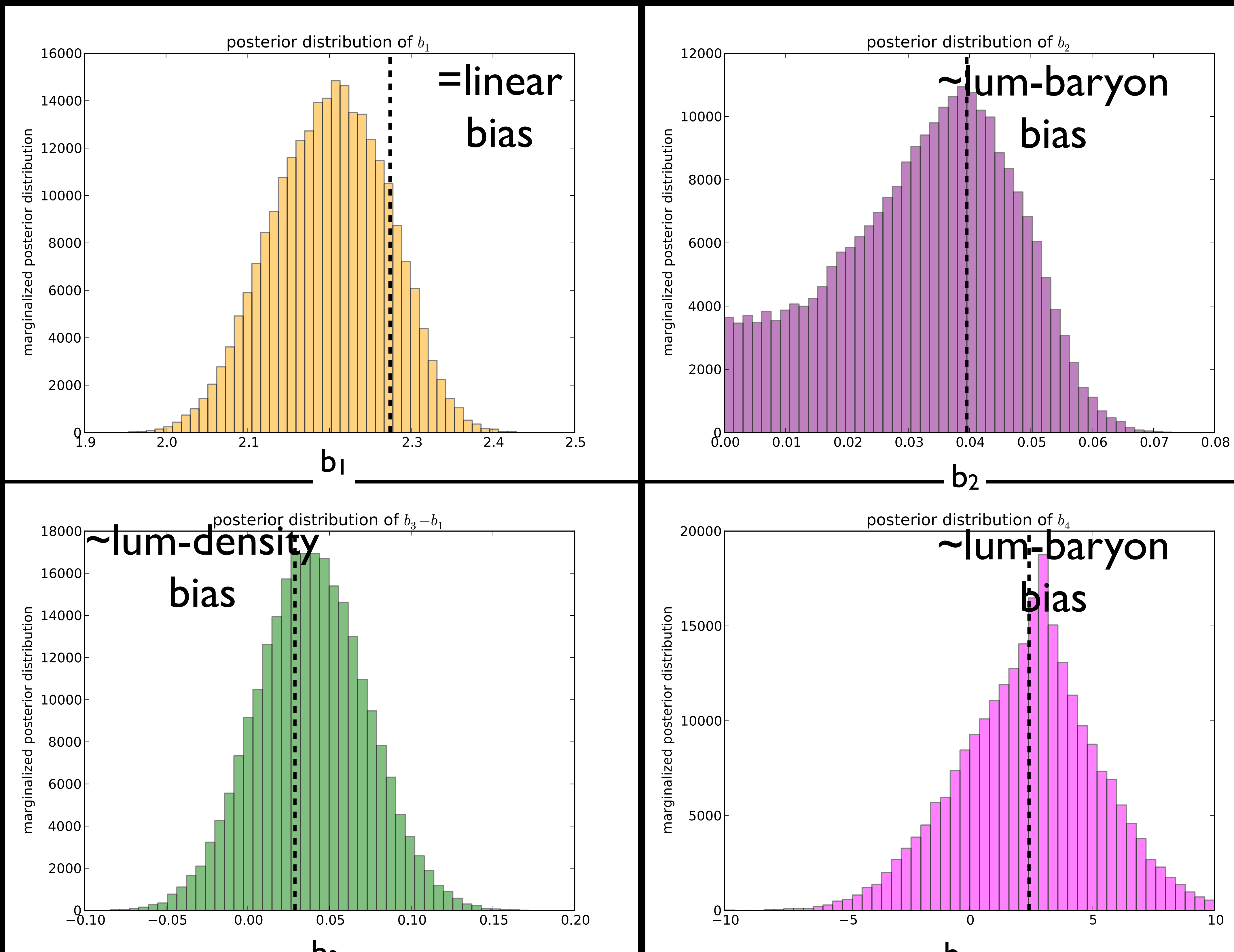
Measurements

~200,000 CMASS galaxies from DR10
0.43<z<0.7

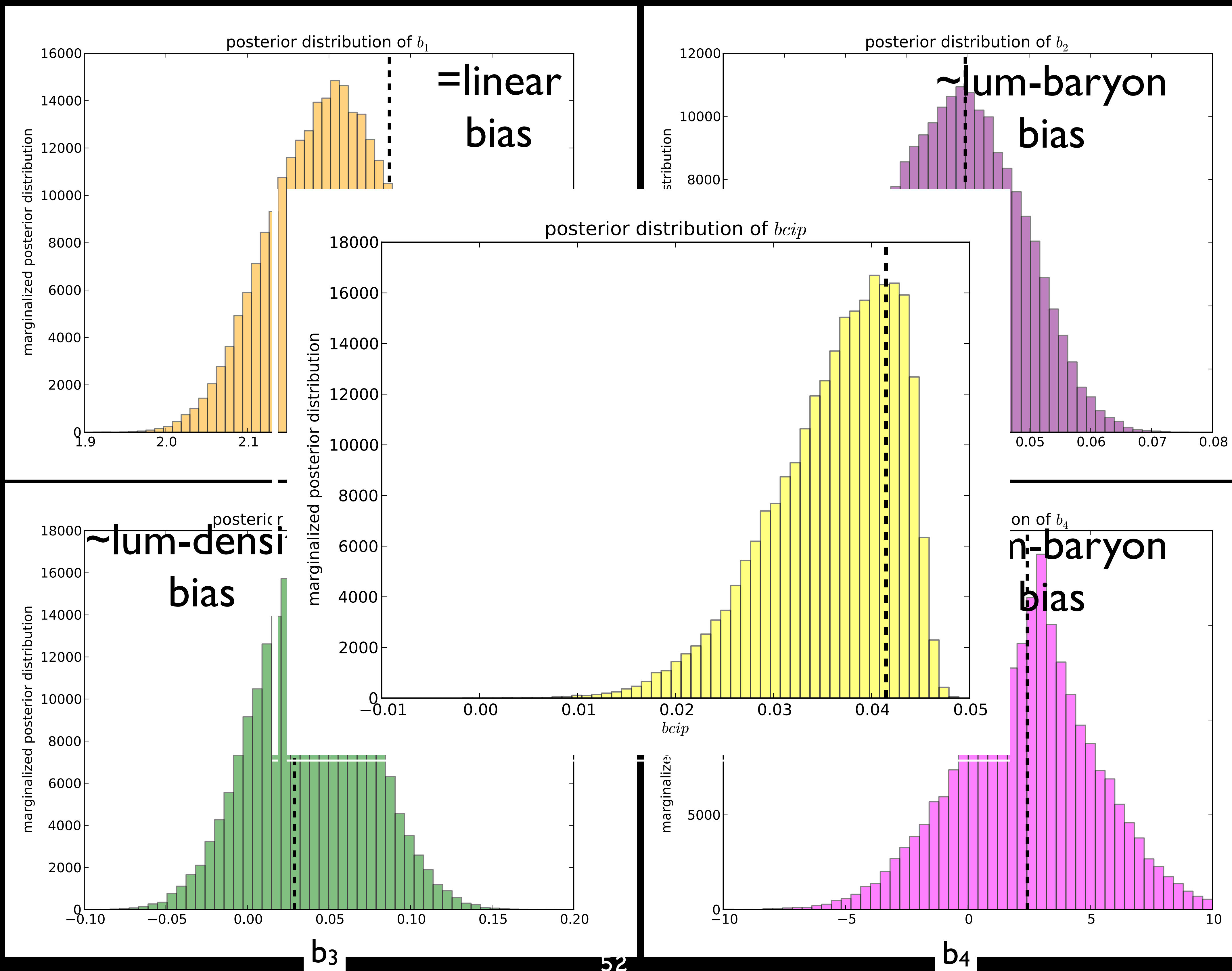




Results: Marginalized Parameter Constraints



Results:
Marginalized Parameter Constraints



Conclusions - III

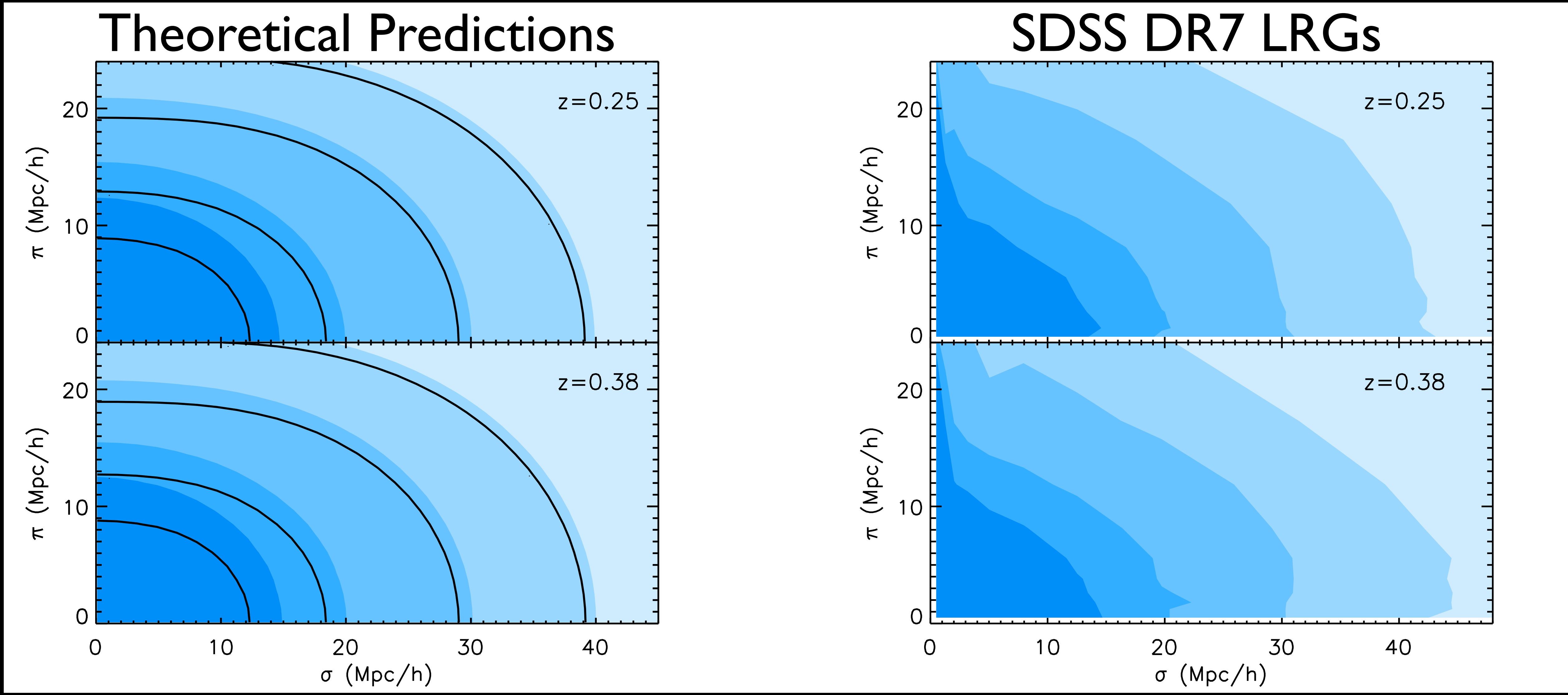
- Measured the luminosity and position 2pcf's
- Confirmed the theoretical prediction of Barkana & Loeb
- The measurement of b_L is a new quantity in galaxy formation, a combination of the way in which the luminosity of a galaxy depends on the baryonic content of the host halo.
- Hint of Compensated Isocurvature Perturbations (preliminary!!)

Large Scale Flows

Measuring coherent motions from redshift distortions

Using SDSS Clusters Song, **CGS**, Nichol, Miller (2010) arXiv:1001.1154

Using SDSS LRGs Song, **CGS**, Kayo, Nichol (2011) arXiv:1006.4630

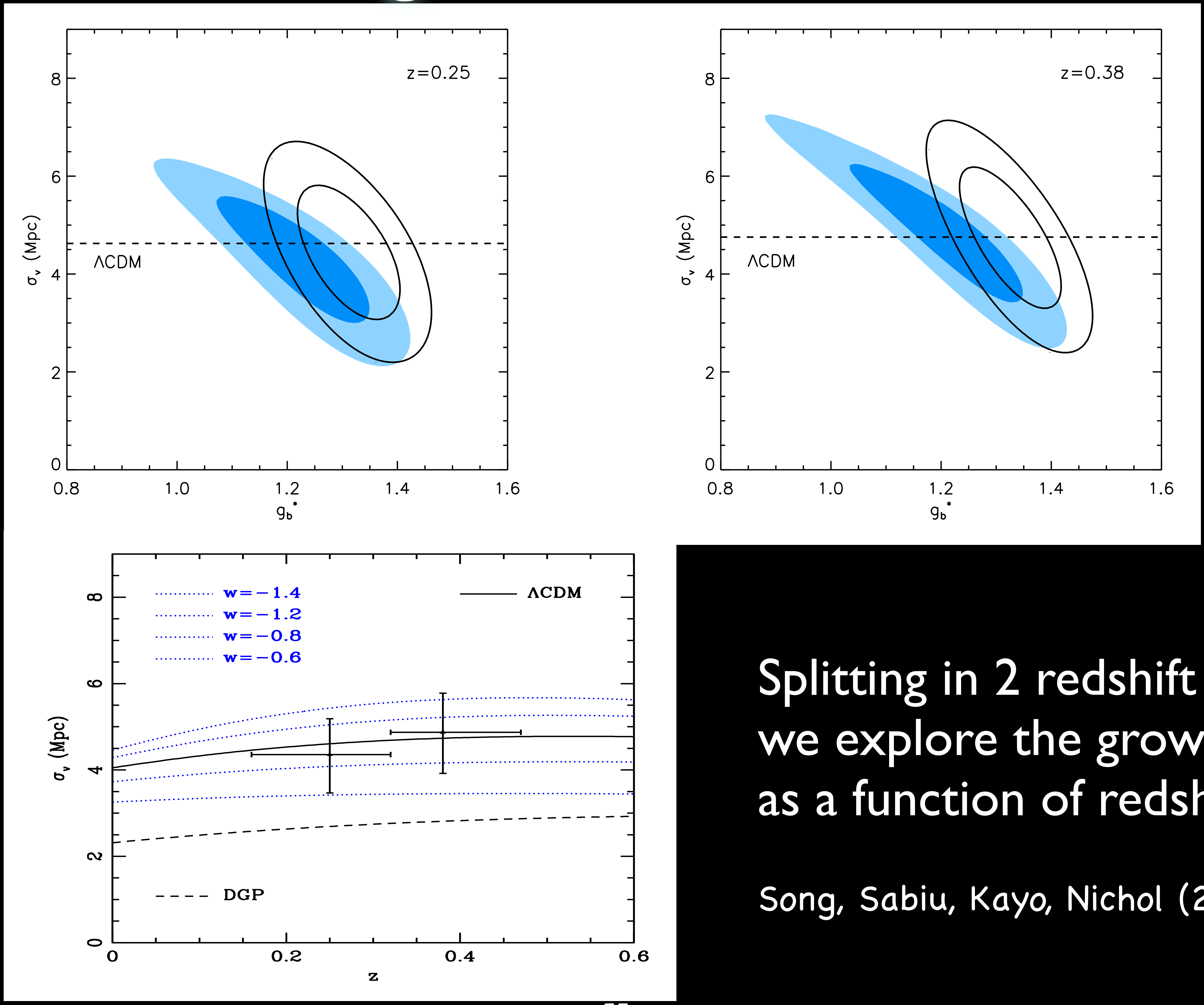


$$\tilde{P}(k,\mu) = \{P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k)\}\, G^{\rm FoG}(k\mu\sigma_p)$$

$$G^{\rm FoG}(k\mu\sigma_p) = \exp\{-(k\mu\sigma_{\rm p})^2\}$$

Streaming model
Scoccimarro '04

Large Scale Flows



Splitting in 2 redshift bins we explore the growth as a function of redshift

Song, Sabiu, Kayo, Nichol (2011)

TNS model

Taruya, Nishimichi, Saito (2010) arXiv: 1006.0699

In going to larger scales and with more precise measurements, theoretical advancements must also be utilized.

$$\tilde{P}(k,\mu) = \left\{P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k)\right\} \exp\left\{-(k\mu\sigma_{\rm p})^2\right\}$$ Streaming model

Kaiser and FoG cannot be so simply separated as the two functions are anisotropic in k-space. Since in general,

$$\langle ABe^C \rangle \neq \langle AB \rangle \langle e^C \rangle$$

TNS proposed an improved model of the redshift-space power spectrum, in which the coupling between the density and velocity fields associated with the Kaiser and the FoG effects is perturbatively incorporated into the power spectrum expression. The resultant expression includes nonlinear corrections consisting of higher-order polynomials.

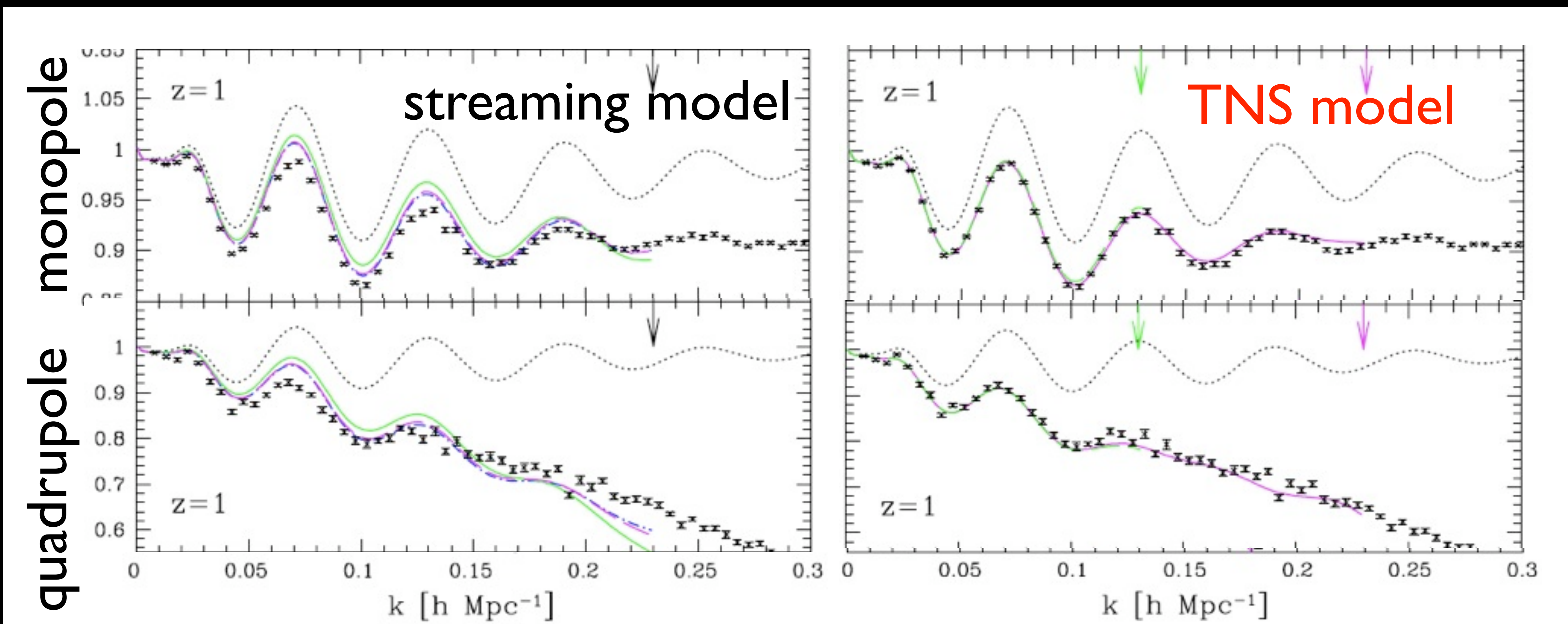
TNS model

$$\tilde{P}(k,\mu) = \{P_{\delta\delta}(k) + 2\mu^2 P_{\delta\Theta}(k) + \mu^4 P_{\Theta\Theta}(k) + A(k,\mu) + B(k,\mu)\} G^{\rm FoG}.$$

$$\tilde{P}(k,\mu) = \sum_{n=0}^{4} Q_{2n}(k)\mu^{2n}\, G^{\rm FoG}(k\mu\sigma_p)$$

$$\begin{aligned} Q_0(k) &= P^{\rm lin}_{\delta\delta}(k) + \delta P_{\delta\delta}(k), \\ Q_2(k) &= 2P^{\rm lin}_{\delta\Theta}(k) + 2\delta P_{\delta\Theta}(k) + C_2(k), \\ Q_4(k) &= P^{\rm lin}_{\Theta\Theta}(k) + \delta P_{\Theta\Theta}(k) + C_4(k), \\ Q_6(k) &= C_6(k), \\ Q_8(k) &= C_8(k), \end{aligned}$$

A(k, μ) andB(k, μ) terms are the nonlinear corrections, and are expanded as power series of μ, including the powers up to μ_6 for the A term and μ_8 for the B term.



Broadband Alcock-Paczynski test exploiting redshift distortions

Song, Okumura, Taruya (2013) arXiv:1309.1162

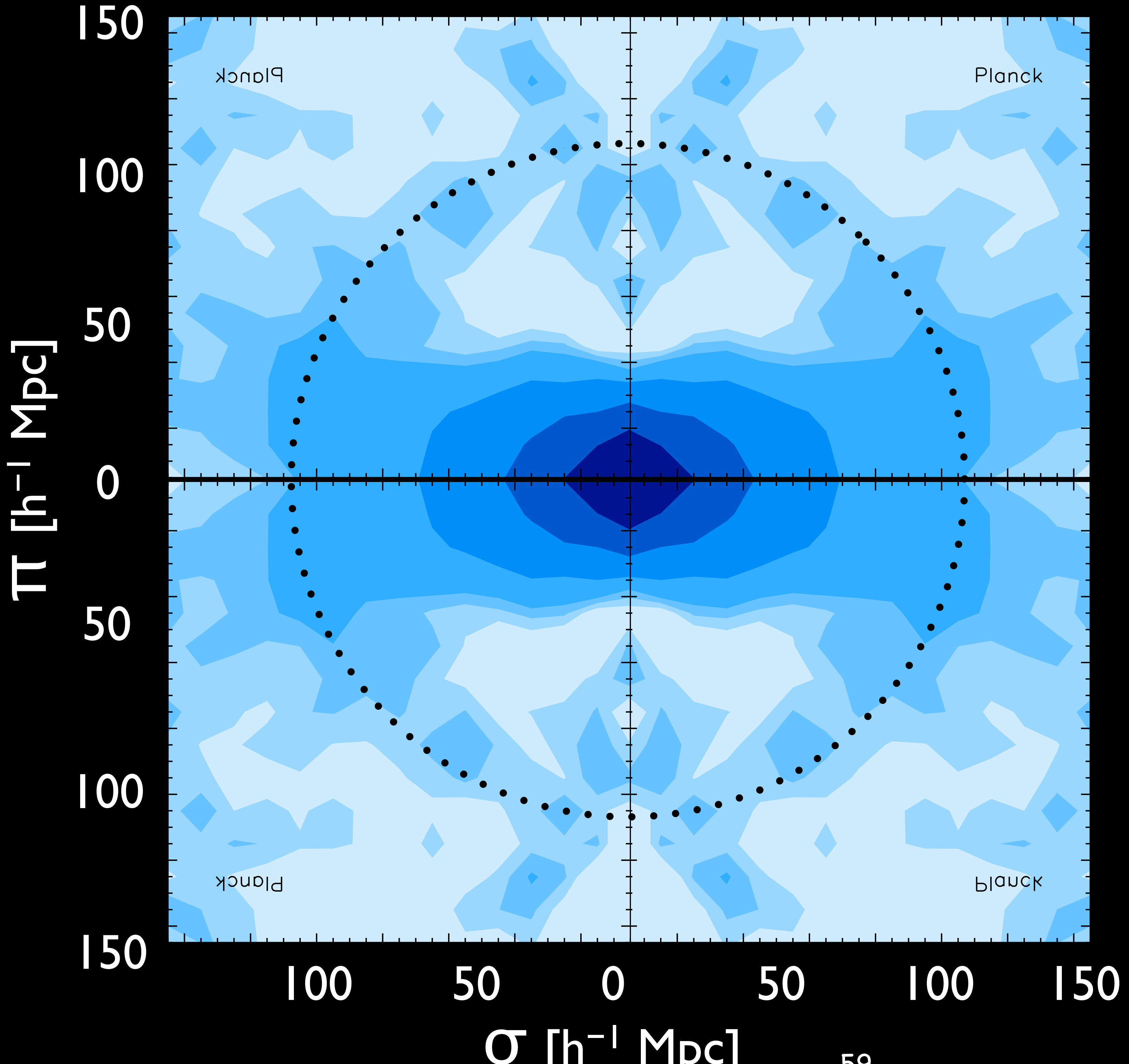
Building on the work of TNS, they show the feasibility of constraining both growth and geometry with current data and future spectroscopic data.

The BAO in 2D forms a circle that remains unchanged due to variations in the galaxy bias and/or coherent motion. While it varies transversely and radially with respect to D_A and H^{-1} respectively.

This sensitivity to the orthogonal scales provides the extra information that enables galaxy clustering alone to place constraints on cosmology and the gravitational model.

This work: 2D clustering on large scale

Linder, Oh, Okumura, Sabiu, Song (2013) arXiv:1311.5226



BOSS CMASS DR9

264,283 galaxies

target selection designed for "constant stellar mass" sample

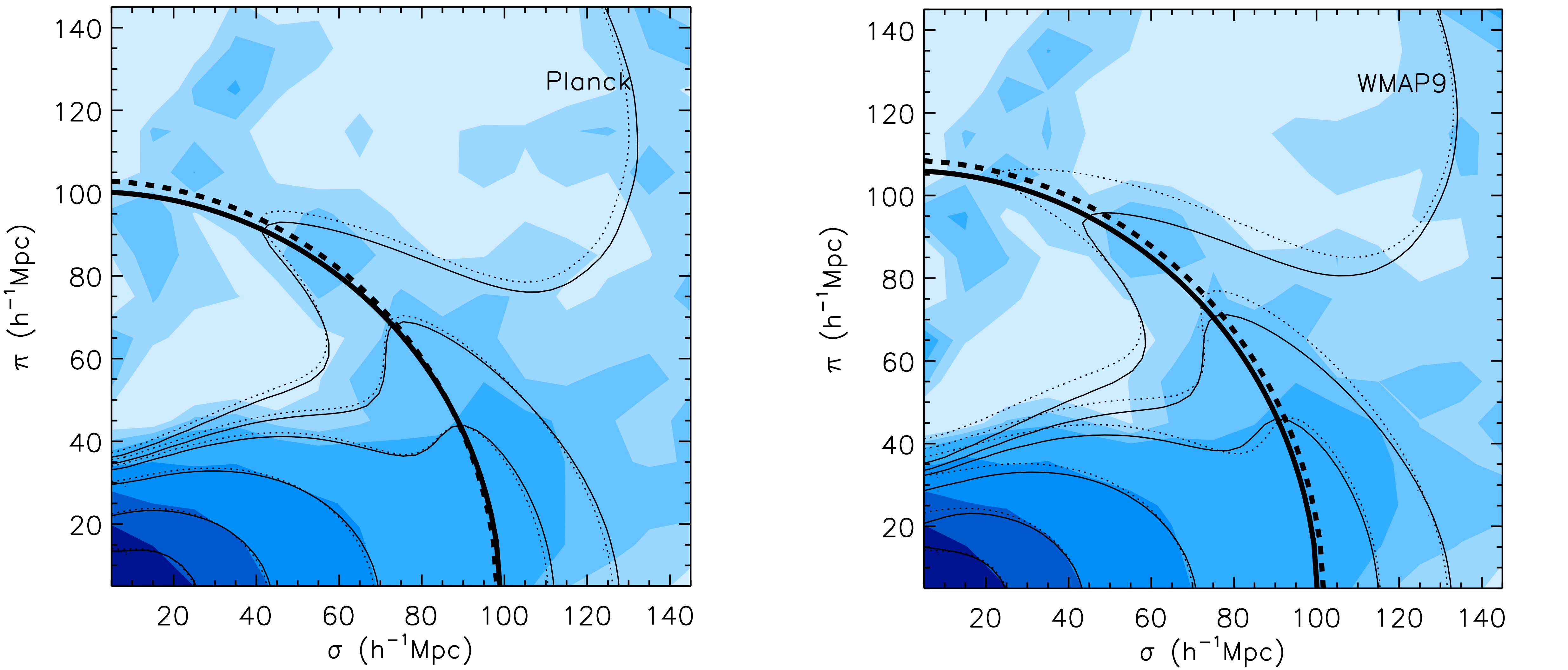
0.43<z<0.7

limiting magnitude of r ~ 22.5

Veff ~ 2.2 Gpc3

Alcock-Paczynski Effect

Fitting the improved TNS model we obtain these fits to the data.

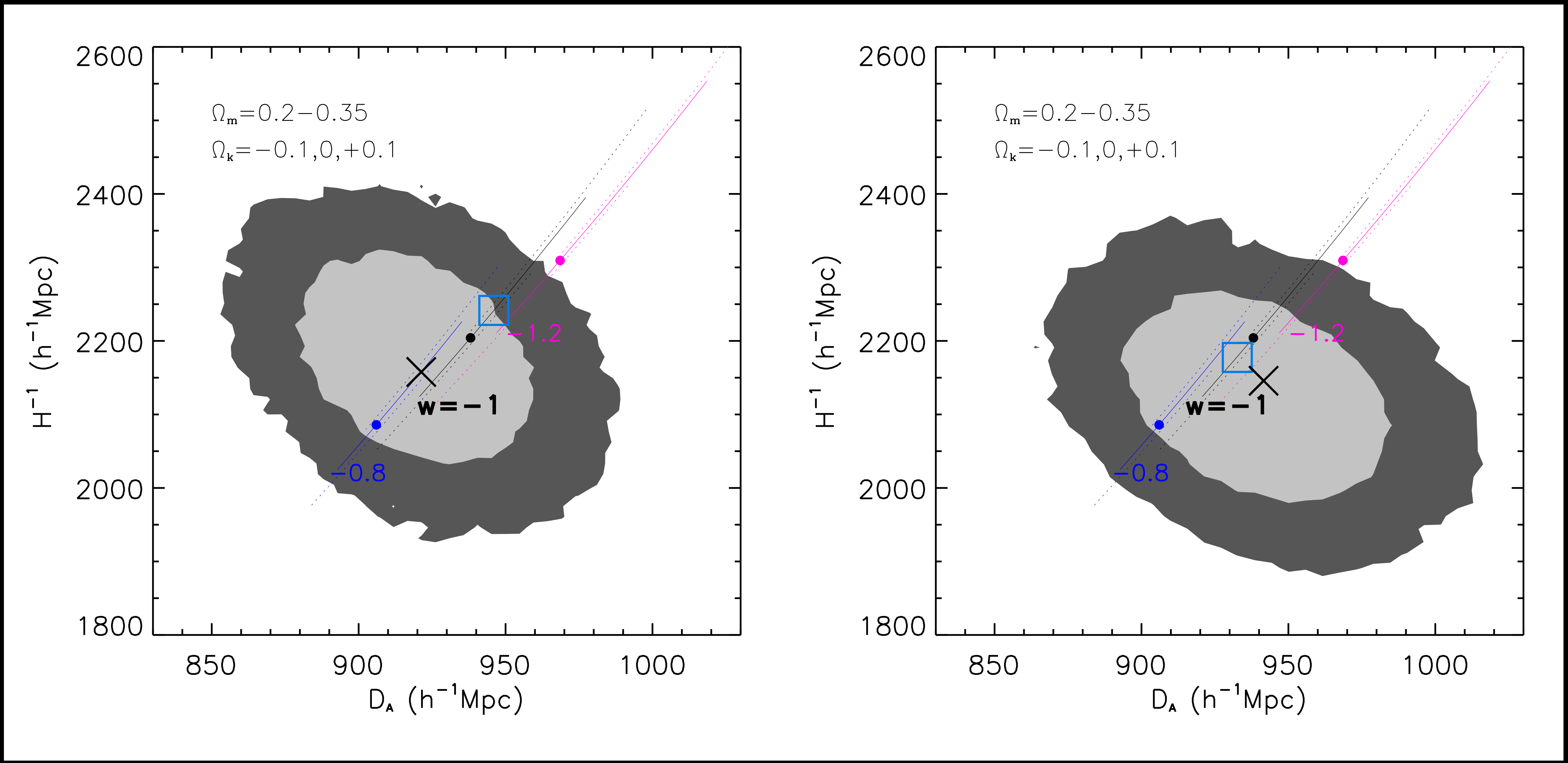


Parameters	Fiducial values With Planck prior	Measurements
$D_A\,(h^{-1}\,\mathrm{Mpc})$	932.6	$939.7^{+26.7}_{-32.6}$
$H^{-1}\,(h^{-1}\,\mathrm{Mpc})$	2177.5	$2120.5^{+82.3}_{-100.6}$
G_b	–	$1.11^{+0.07}_{-0.10}$
G_Θ	0.46	$0.47^{+0.10}_{-0.07}$
$\sigma_p\,(h^{-1}\,\mathrm{Mpc})$	–	$1.2^{+4.0}$

Parameters	Fiducial values With WMAP9 prior	Measurements
$D_A\,(h^{-1}\,\mathrm{Mpc})$	946.0	$916.2^{+27.2}_{-25.4}$
$H^{-1}\,(h^{-1}\,\mathrm{Mpc})$	2241.5	$2163.1^{+102.0}_{-85.8}$
G_b	–	$1.07^{+0.07}_{-0.09}$
G_Θ	0.44	$0.51^{+0.09}_{-0.08}$
$\sigma_p\,(h^{-1}\,\mathrm{Mpc})$	–	$1.0^{+4.6}$

Testing Cosmology

Constraints in H-DA plane

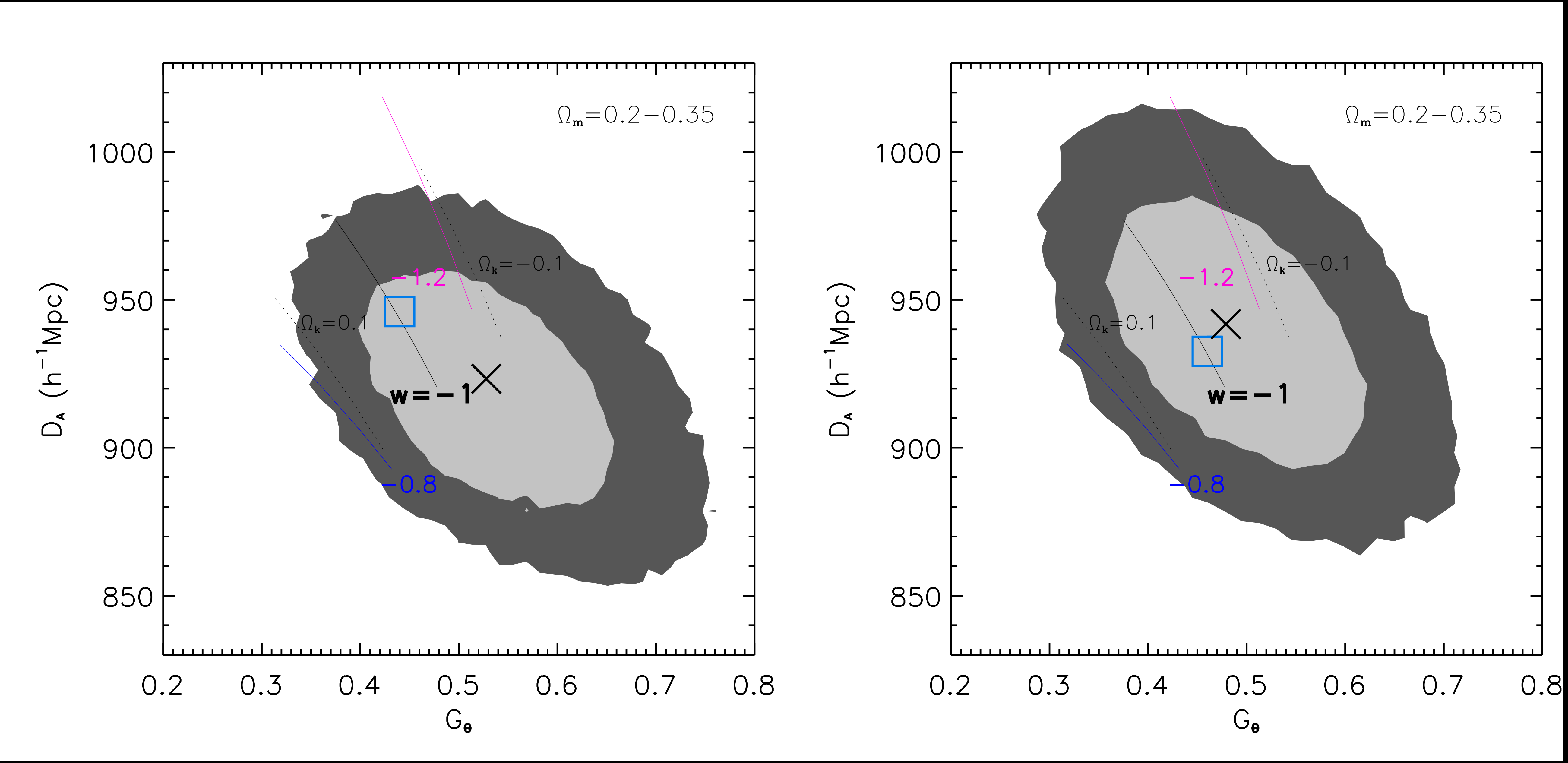


WMAP9
early universe prior

PLANCK
early universe prior

Testing Cosmology

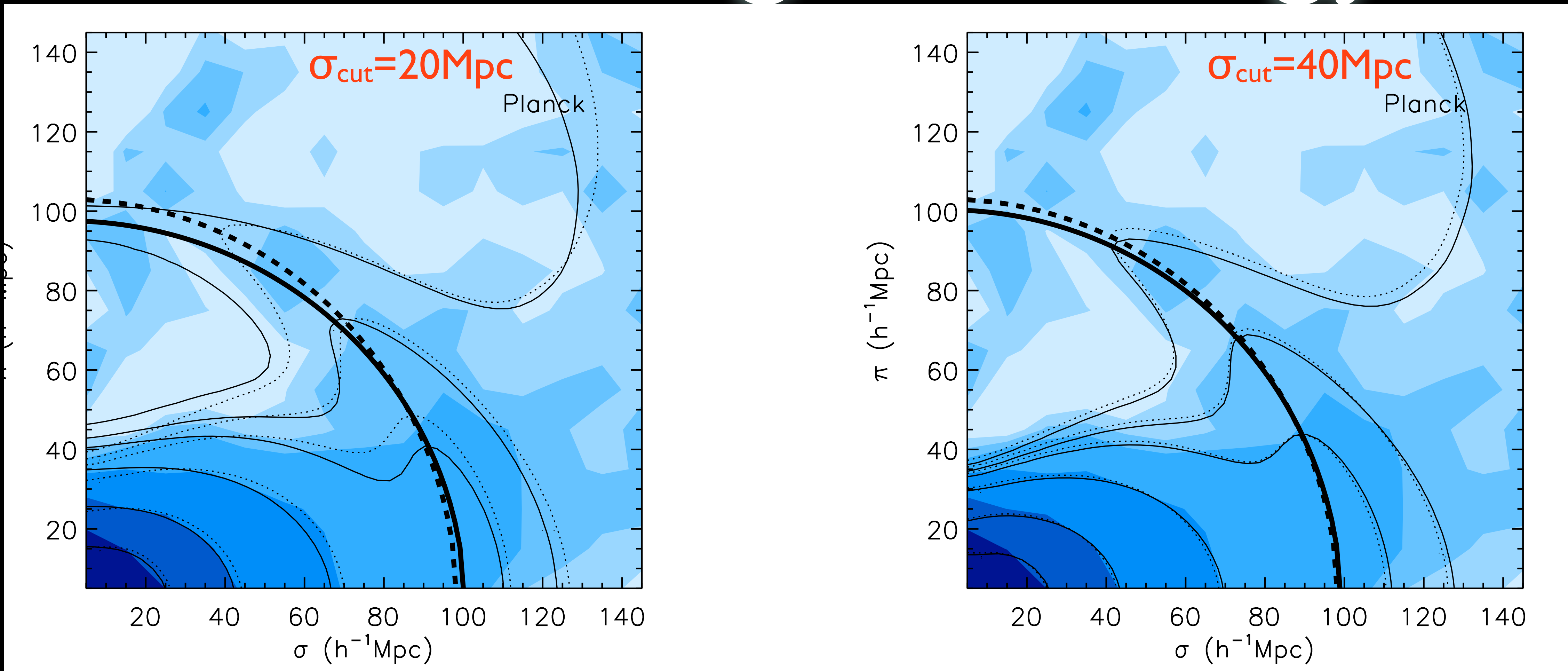
Constraints in DA-G plane



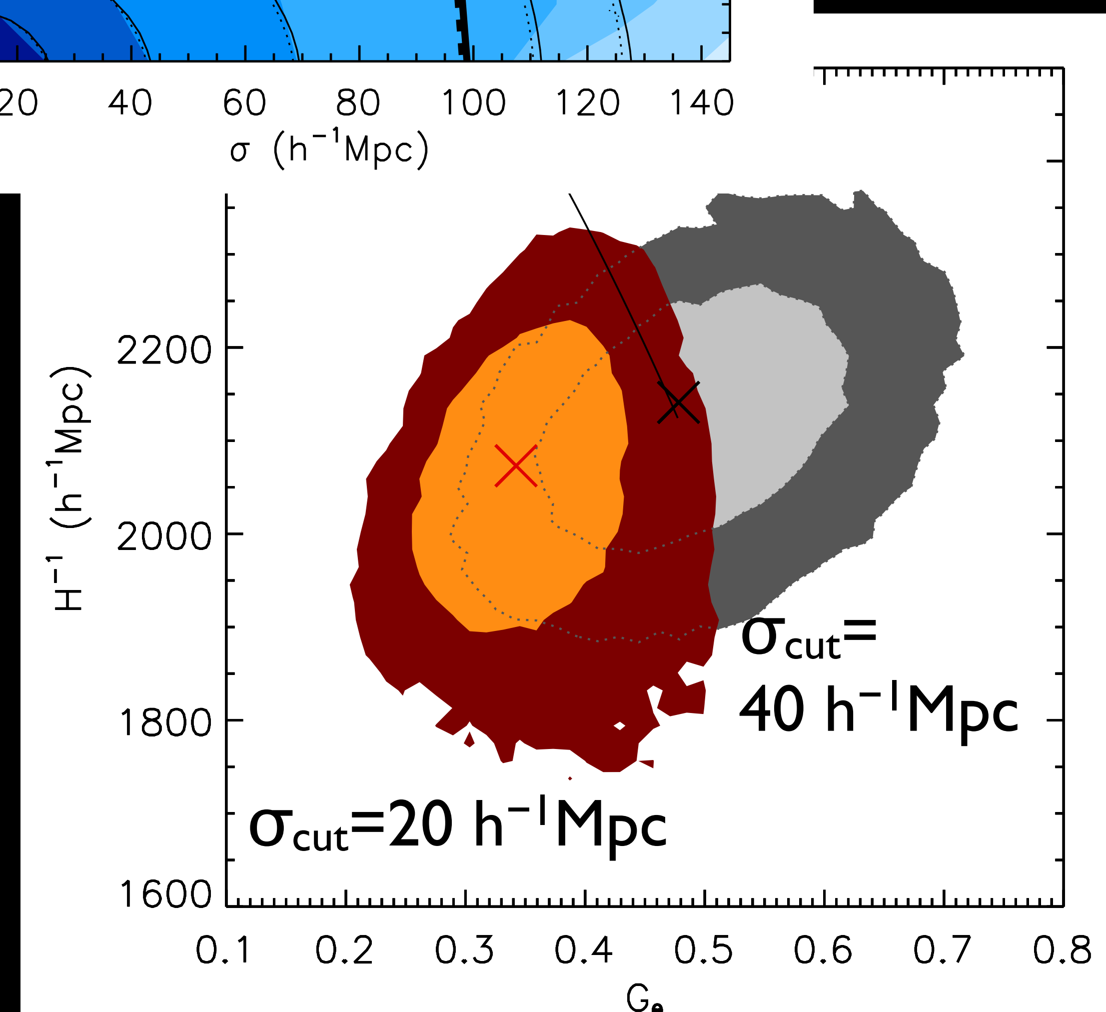
WMAP9
early universe prior

PLANCK
early universe prior

Testing Cosmology



Using data to smaller, non-linear scales, we do find deviations. In particular, G_Θ rapidly becomes slightly underestimated, with values of 0.42 for a cutoff at $\sigma_{cut} = 30\ h^{-1}$ Mpc and 0.34 for $\sigma_{cut} = 20\ h^{-1}$ Mpc.

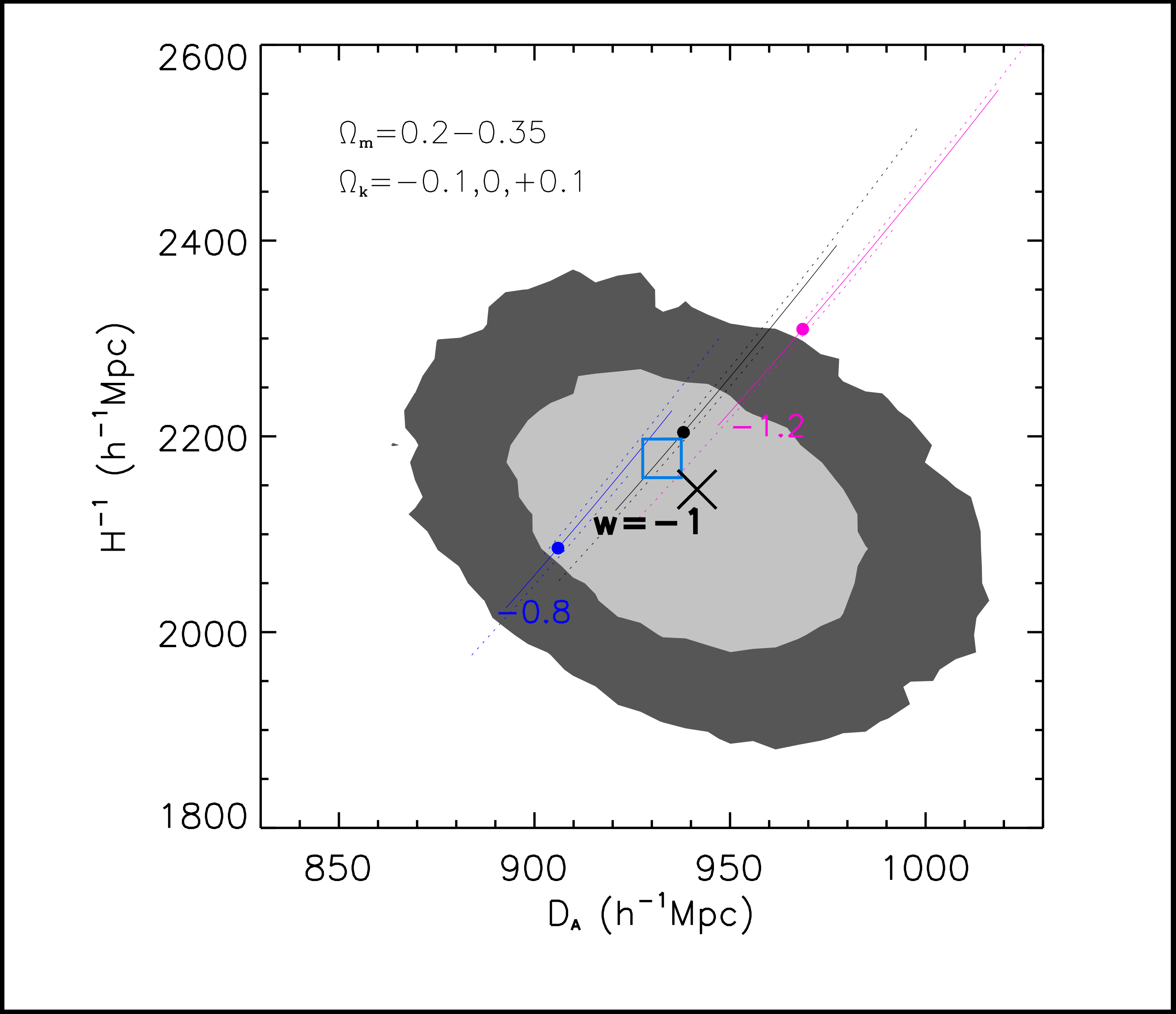


DR11 update

Constraints in H-DA plane

X - best fit
□ - Planck pred.

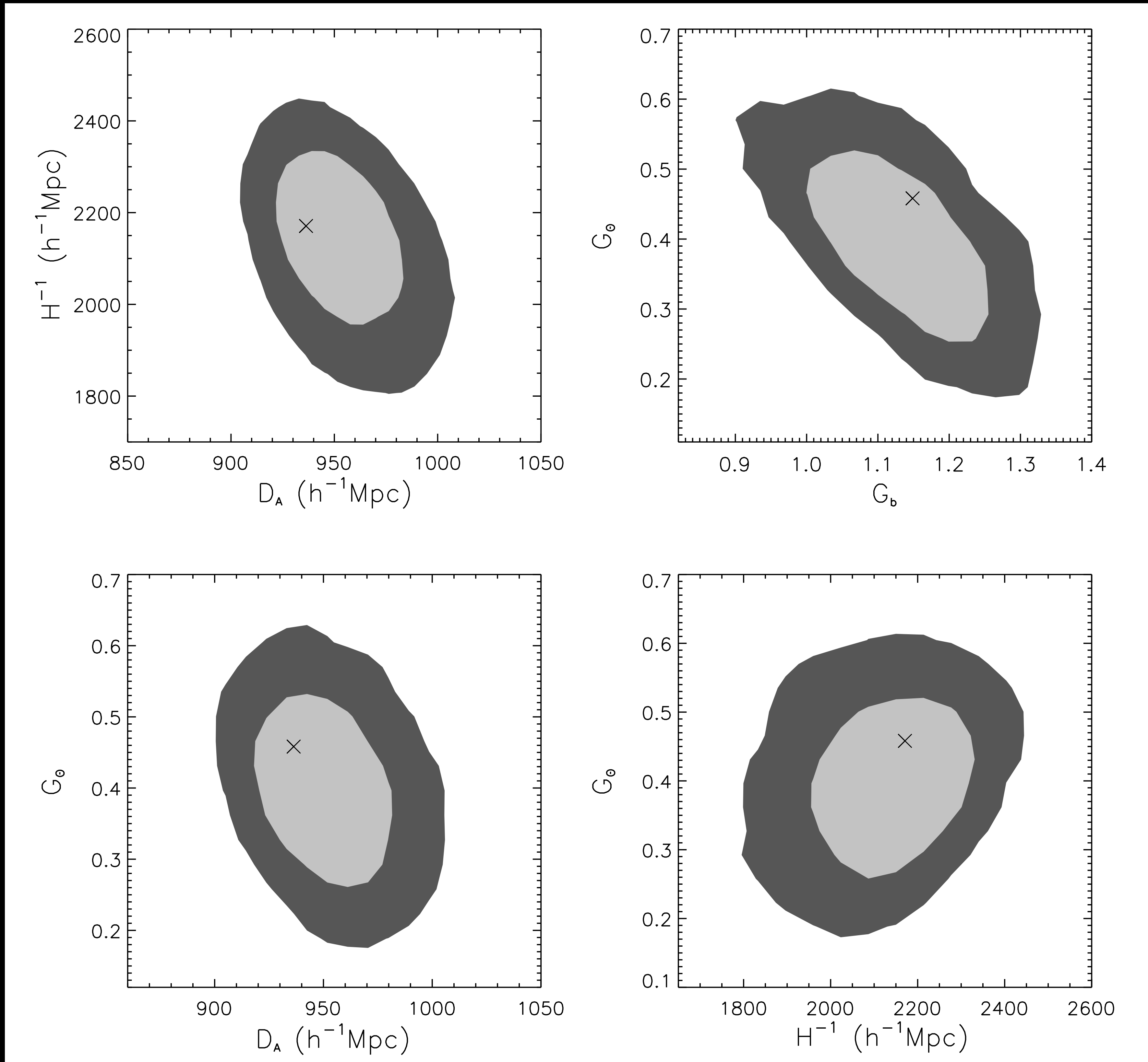
Lines denote different w values with extent coming from variation in Om and Ok



DR9

Testing Cosmology

2D Constraints - DR11



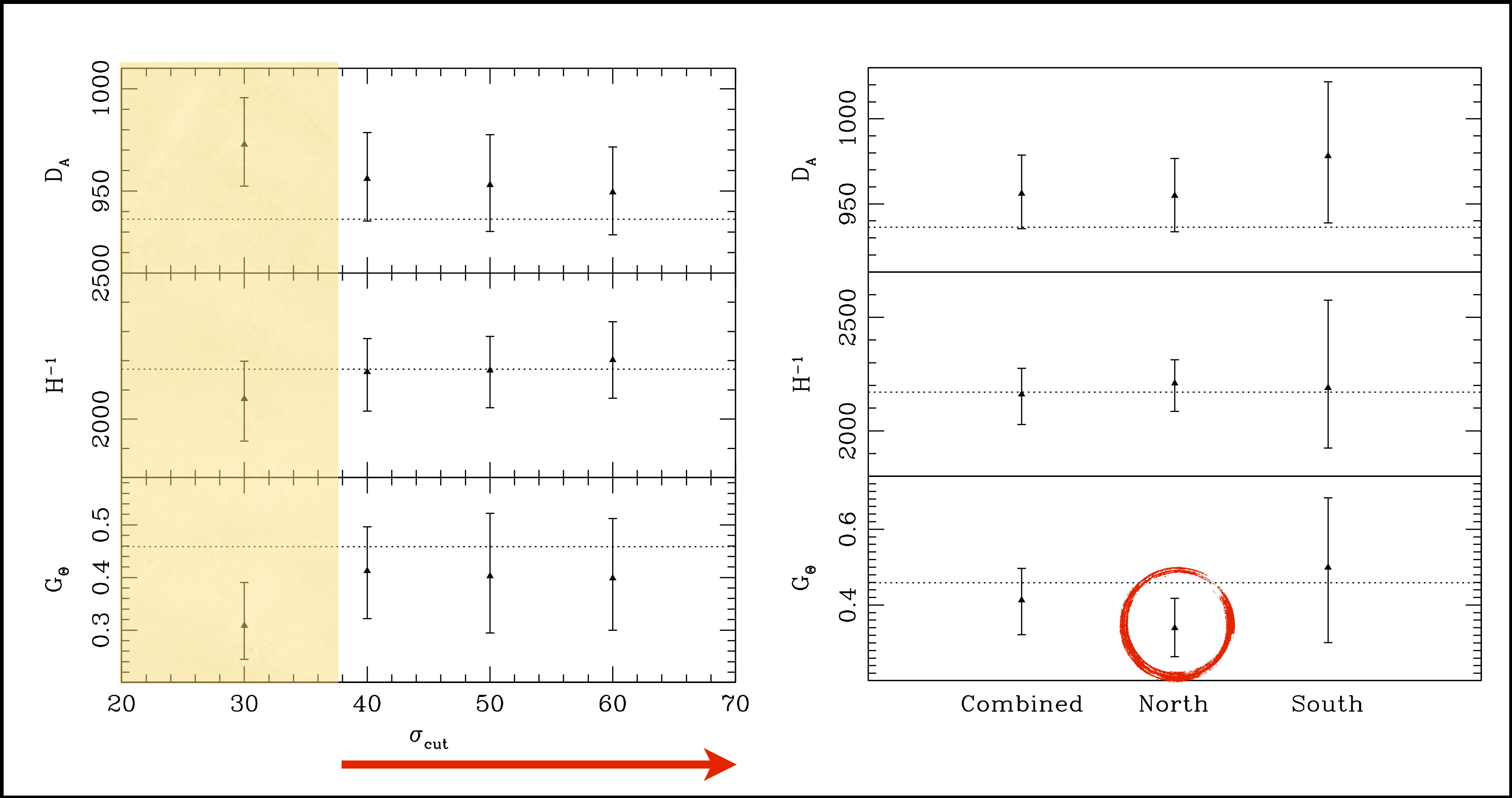
- Using PLANCK early universe prior

- Results consistent with PLANCK input model

- No deviation from GR+LCDM within observational limits

Testing Cosmology

Stability of small scale cut-off   Combined/North/South



Alcock-Paczynski Effect

Theoretically the geometric distortions of the AP effect can be modeled exactly:

$$\xi^{\rm fid}(r_\sigma, r_\pi) = \xi^{\rm true}(\alpha_\perp r_\sigma, \alpha_\parallel r_\pi),$$

$$\alpha_\perp = \frac{D_A^{\rm fid}(z_{\rm eff})}{D_A^{\rm true}(z_{\rm eff})}, \qquad \alpha_\parallel = \frac{H^{\rm true}(z_{\rm eff})}{H^{\rm fid}(z_{\rm eff})},$$

D_A, H vary peak positions off the BAO ring.

Growth rates G_b, G_θ, shift peak position along BAO ring. But display different behavior in and small and large mu.

These different shifting allows us to separate and constrain the various observables.